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RESEARCH INVESTIGATIONS ON PHOTO FACSIMILE TRANSMISSION TECHNIQUES

REPORT NO. 2

SECOND QUARTERLY PROGRESS REPORT
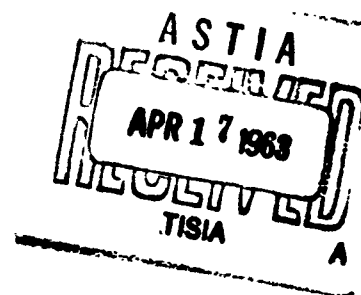
1 OCTOBER 1962 THRU 31 DECEMBER 1962

CONTRACT NO. DA36-039 sc-90862

DEPARTMENT OF ARMY PROJECT NO. 3A99-12-001

U.S. ARMY SIGNAL RESEARCH AND DEVELOPMENT LABORATORY
FORT MONMOUTH, NEW JERSEY

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REPORT NO. 25,069

THE MARQUARDT CORPORATION

16555 SATICOY STREET   VAN NUYS, CALIFORNIA

4 April 1963
Ref: 283/885/2665

Gentlemen:

Subject: Photo Facsimile Transmission Techniques
          Contract No. DA 36-039 SC-90862
          Second Quarterly Progress Report

1.   In accordance with Contract No. DA 36-039 SC-90862
the Second Quarterly Progress Report is being forwarded to
you.

2.   This report covers the period from 1 October 1962
through 31 December 1962.

                              THE MARQUARDT CORPORATION

                              Thomas G Bek HRW
                              Thomas G. Bek, Manager
                              V. N. Contract Administration Section

TGB:WHH:bg

RESEARCH INVESTIGATIONS ON

PHOTO FACSIMILE TRANSMISSION TECHNIQUES

Report No. 2

Second Quarterly Progress Report

1 October 1962 thru 31 December 1962

Contract No. DA 36-039 SC-90862

Signal Corps Technical Requirements No. SCL-4362A
dated 2 February 1962

Department of Army No. 3A99-12-001

Objective: A research investigation leading to the development
of techniques useful in the design of a facsimile scanner which
shall be capable, upon command, of capturing an optical image,
scanning it with high resolution and storing it or directly
transmitting it via radio to a facsimile recorder.

Report prepared by

W. H. Hell
B. Case
J. A. Howard
R. M. Ransier
C. Schuppe
J. A. Widmer

THE MARQUARDT CORPORATION
VAN NUYS, CALIFORNIA

Report No. 25069

TABLE OF CONTENTS

LIST OF FIGURES AND TABLES

TABLES

PURPOSE

The theoretical and experimental research study under this contract is directed toward investigating pertinent materials and components with the purpose of evolving a new design concept for an advanced image transducer. Major emphasis in the study is on (1) photosensitive material having the properties of storage and erasure, (2) component techniques for achieving high resolution, fast and accurate readout of the stored information and (3) image transducer system analyses. The ideas, techniques and data evolved in the study will be applied to the generation of a design recommendation for the construction of a feasibility model of an advanced image transducer.

ABSTRACT

The major effort during the second quarterly period on
advanced photofacsimile transmission techniques has been directed
toward a comprehensive survey of image transducing materials.
In addition, work was continued on system analysis and component
technique investigations.

Representative data for describing scenes was acquired.
While no attempt was made to classify all possible scenes,
sufficient examples are presented to establish guide-lines for
transducer requirements as functions of active scene irradiance
and of geometry and spectral properties of scene elements.
The image transducing parameter study was continued. Data on
performance characteristics and practical parametric interrela-
tionships of most types of image transducing techniques is
presented.

Several line scanning techniques for the optical readout
of a stored image have been investigated. These techniques
include a programmed matrix light source with a fiber optic
converter to provide a line scan, a flying spot scanner employing
a fiber optic line converter, and the Kaiser Electronic special
line scan facsimile tube. Furthermore, a number of novel mechan-
ical scanner configurations have been conceived.

Two image storage techniques were studied: (1) The
optron (a photoconductor-electroluminophor combination); (2)
the ferrotron (a photoconductor-ferroelectric combination).
The former has achieved   80 lines per inch resolution and 0.1

foot candle sec. sensitivity, while the latter has achieved 250
lines per inch under an illumination of 0.001 foot candles, and
appears more promising as a component for an advanced photo fac-
simile transmission system.

Methods of automatic fabrication of an ordered fiber
optic array for high resolution image dissection were investigated.
The evolution of a device capable of providing fibers in vast
numbers and of the small diameter required for the array contem-
plated would entail a prohibitively costly development, at least
in the near future.

An extensive literature search was made to uncover
materials displaying properties which may make them useful in an
image transducing device. As a result of this search, material
characteristics associated with the phenomena of photoconductivity,
electroluminescence, double-activated phosphorescence, and photo-
tropism are listed. Materials exhibiting properties associated
with the ferro-electric phenomenon have yet to be investigated
in the literature search.

Experiments were made to develop a transparent synthetic
form of hackmanite. In these experiments, a novel approach using
elevated temperatures and pressures in the forming process was
employed.

PUBLICATIONS, LECTURES, REPORTS AND CONFERENCES

A. Publications:

       None

B. Lectures:

       None

C. Reports:

       "Research Investigations on Photo Facsimile Transmission
    Techniques", Monthly Progress Summary, October 1962, Reference
    Letter 283/855-00/2431, dated 5 November 1962.

       "Research Investigations on Photo Facsimile Transmission
    Techniques", Monthly Progress Summary, November 1962, Reference
    Letter 283/855-00-2479, dated 6 December 1962.

C. Conferences:

       Date: 1 October 1962
       Location: Polacoat, Inc., Blue Ash, Ohio
       Subject: Research on Phototropic Materials
       Present: John F. Dryer, Polacoat, Inc.
                    Robert W. Harries, "   "
                    J. A. Widmer, The Marquardt Corporation

       Resume: The use of hackmanite as a photropic information
storage medium is feasible. Theoretical and experimental research
should be continued to determine methods of practical application.

       The use of photochromic dyes as storage media is less
promising than the use of hackmanite because of the gradual deterior-
ation of the phototropic material due to unwanted side reactions.

       Date: 2 October 1962
       Location: Horizons, Inc., Cleveland, Ohio

Subject: Possible application of photochromic dyes as
            a high density information storage medium.

Present: Robert Sprague, Horizons, Inc.

            Eugene Wainer,   "   "

            J. A. Widmer, The Marquardt Corporation

Resume: The research program at Horizons, Inc. has
uncovered many interesting photochromic dyes oriented toward photo
recording and picture formation. At the current stage of development,
none are applicable to use in the image transducer on the subject
contract as a consequence of lack of erasure capability.

Date: 10 October 1962

Location: Bureau of Standards, Washington, D. C.

Subject: Instrumentation for measuring characteristics
            of phosphors.

Present: Dr. Telle, NBS

            J. A. Widmer, The Marquardt Corporation

Resume: Instrumentation for measuring the photometric
           characteristics of phosphors was discussed.

Date: 19 Decemoer 1962

Location: Optics Technology, Belmont, Calif.

Subject: Fiber Optics fabrication

Present: Dr. Kapony, Optics Technology Incorporated

            B. Case, The Marquardt Corporation

            R. Ransier, The Marquardt Corporation

Resume: The state-of-the-art in fabricating fiber optics
does not now permit the automatic and economical construction of an
ordered fiber optics array employing the vast number of fibers necessi-
tated by the application as a readout component of the image transducer
for the subject contract.

I.   INTRODUCTION

        In order to improve on the present state-of-the-art in
image transducing, broad research work to develop new approaches
was outlined in the First Quarterly Report in three areas: (1)
system analysis; (2) component research; (3) materials study. As
the work progressed, the least promising materials and techniques
were to be eliminated, resulting in a systematic narrowing of the
possible approaches.

        In the area of system analysis, the two fundamental
problems are: (a) defining desirable image transducer performance
characteristics; (b) defining their theoretical and practical
limitations. During the first quarter, scene composition studies
were effected and a study of parametric interrelationships was
initiated. In order to provide insight into the performance
characteristics and practical limitations of image transducers, a
survey of the state-of-the-art in existing systems was needed.
This survey would also be useful in establishing design criteria
for the advanced system.

        Under the category of component research, it was pointed
out in the First Quarterly Report than an image transducer system
requires components capable of image retention and readout. One
of the requirements of a system is that the storage medium for
image retention be capable of erasure. Only recently have new
developments along this line been made. These developments
(thermoplastic and photostatic tapes, optron and ferrotron)
should be investigated t determine their applicability to the

problem at hand. If they are not suitable, an entirely new approach
based on the findings of the material study may be required. For
image readout, the matrix switching method and the line or raster
scan method are considered. Evaluation of the former awaits the
outcome of the material survey. Raster scan suffers from a basic
limitation on resolution capability which is a function of the
ratio of scan length to beam width. Improved resolution of elec-
tronic scanning techniques can be achieved through the use of an
ordered fiber optic array. Another possible method for improving
the resolution of electronic scanning techniques consists of
converting the elements of a raster into a single line, with
orthogonal scanning accomplished by moving the image with respect
to the line.

The selection of materials is based upon material
characteristics and upon the configuration of the entire image
transducing system. It was found during the first quarter that
the available literature on materials often contained data of a
descriptive nature, devoid of information required for application
to an image transducer (e.g., quantum efficiency). For this
reason, experiments are required in order to obtain the needed
parameters. Experiments are time-consuming, however, and must
be limited to the most promising materials. It was indicated in
the First Quarterly Report that hackmanite in its natural form
is not suitable for use in the contemplated image transducer.
Therefore, a decision was made to investigate the possibility of
fabricating a synthetic form of the material.

Since no specific material has been selected for use
in an image transducer, the approach was to initially consider all
materials exhibiting suitable properties associated with the image
transducing phenomena. In the previous report the number of
suitable phenomena has been narrowed, thereby reducing the materials
that can be considered for evaluation. Ultimately, as a result of
this process of elimination, the most promising of the many materials
will be selected for consideration in an advanced image transducer
system.

II   SYSTEM ANALYSIS

A.   SUMMARY

During the last quarter, the following has been accomplish-
ed in the area of systems analysis:

(1) Completion of scene composition studies
(2) Continuation of image transducer parameter studies

The specific requirements for defining the composition of
a scene were detailed in the First Quarterly Progress Report. During
this quarter, specific data were gathered to allow a full description of
the scene and completion of the analytical research study in line with
the original objectives. This information consists of representative
data for evaluating the irradiance in many active scenes and an expanded
study of the relative importance of the geometry and spectral properties
of the scene elements. It is shown that these data used in conjunction
with the scene categorization method reported in the First Quarterly Pro-
gress Report allow the complete specification of many representative scenes.
No attempt was made to completely classify all scenes since this is beyond
the scope of the present study. However, several representative examples
of scene categorization are given.

During the past quarter, the transducer parameter study has
been concered with: (1) establishing ranges for the several parameters
based on practical transducer limitations; and (2) obtaining a more com-
prehensive picture of the relative importance of the parameters as a
function of transducer mission in order that trade-off possibilities can
be delineated. To meet these objectives, a survey of the present state-of-
the-art of image transducers has been conducted. The results of this survey
briefly summarize the characteristics of image transducer systems and discuss
the interrelation of the various parameters from a practical viewpoint.

B. SCENE COMPOSITION PHYSICAL BASIS

The specific requirements for a more extensive review and presentation of radiometric data describing a range of passive and active scenes was made clear in the First Quarterly Progress Report. Although some average or representative data for active (transient luminance pattern) and passive (steady state) scenes were reported, the very large literature of this technical area was hardly touched. During the past quarter, this analytical research study has been continued and been brought to effective completion in the light of the objectives of the preliminary study. Scenes were defined in the context of a flow diagram in the last report. In review, the scene characteristics are:

    a. Radiant excitation - Quantity, directional character (collimated to perfectly diffused) temporal variation and spectral distribution of the radiant flux incident on the scene elements.

    b. Geometric Detail - angular size, shape, and orientation of significant detail (dictated by the acuity of the read-out instrumentation) in the scene in terms of scene aspect (distant, semi-distant, etc.)

    c. Spectral Properties of Scene Elements - the spectral reflectance, absorptance, and transmittance of significant detail in the scene; classification in terms of gray (non-selective) and spectral range (selective or variant in wavelength).

Additional specific data identified with the above
scene properties are reported here to allow further development of
the unique classification system reported earlier. This physical
data for ranges of scenes with various G (Geometry), E (Excitation),
and S (Spectral) characteristics provides the input information
necessary for the evaluation of a variety of image transducing
effects. In this section, the required G, E, and S data is reported.
This is, of course, a preliminary study that cannot include all
available data but the presentation is so structured that additional
significant data can be introduced as it becomes available.

1. Radiant Excitation

Multiple, highly variable radiant sources are
characteristic of outdoor active reconnaissance scenes while passive
scenes (e.g., the photographic image) are generally illuminated with
controlled sources of well-known spectral, temporal, and directional
properties. For this reason, the more demanding aspects of illumi-
nants for the active scene are treated here. When direct solar
irradiation is available to a scene within the earth's atmosphere,
both the collimated sunlight and the scattered skylight contribute
to the luminance pattern viewed by the image transducer. In addition
to differences in quantity and quality (spectral distribution),
direct solar illumination and scattered skylight are most strikingly
distinguished by their directional aspects. Direct sunlight is
effectively collimated (sun subtends an angle of 0.5 degrees) and
thus produces strong shadows in a typical scene. Differently, the
sky is a source of effectively infinite dimensions (occupies half
space with respect to the horizontal plane) and is thus a diffuse
illuminant capable of producing only weak, poorly defined shadows.

Objects of scene elements that receive no direct sunlight are often
largely illuminated by the diffuse skylight of a strongly blue
character relative to the effectively white direct sunlight.

Direct sunlight and skylight are strongly effected
by the atmosphere. Although the effective height of the earth's
atmosphere is about 60 miles, the path length through the atmosphere
in the direction of the zenith is equivalent to only about 5 miles
with the same gases compressed to sea-level conditions. At directions
away from the zenith, the effective path length through the atmosphere
increases and the direct sunlight reaching the earth's surface is
diminished. Water vapor, condensed water vapor, dust particles,
smoke, etc., are the principal contaminants of the atmosphere that
influence the sunlight and scattered skylight on the scene. Rayleigh
scattering in the atmosphere gases accounts for the blue sky while
the Mie scattering function describes the skylight scattered by
particles.

a. Direct Sunlight

As suggested above, the direct solar illumin-
tion at the scene within the earth's atmosphere is dependent on:

    (1) Variations in solar emission with time
    (2) Seasonal differences in the earth-sun
         distance (7% difference in flux intensity
         from January to July)
    (3) Amount of water vapor as a function of
         latitude, altitude, distance from the
         oceans and gaseous temperature.
    (4) Dustiness or haziness of the atmosphere

(5) The zenith distance of the sun for a
particular location which is a well
defined function of the latitude, time
of day, and time of year.

(6) The altitude above sea level. Taking all
these factors into account, the data of
Figure 1 contain proposed standard solar
irradiance curves.

In Figure 2, the spectral solar irradiance on a plane normal to the
sun's rays is shown with the number of air masses through which the
flux has passed as the parameter. Zero air mass (m = 0) corresponds
to a location outside the earth's atmosphere. When the sun is at
the zenith, the air mass is taken as unity. These curves are appli-
cable to a scene at sea level with some condensed water vapor present
and a relatively small amount of dust. The change in curve shape
with increasing air mass (atmospheric path length) is related to
increased scattering.

Using the standard photopic response function,
the spectral curves of Figure 1 can be converted to illumination
curves by an integration process. The results are plotted in Figure 2
which depicts the direct solar illumination at the earth's surface
(sea level) as a function of air mass through which the sun is viewed.
As shown in Figure 2, the experimental values vary somewhat with the
time of year but the average is in good agreement with the computed
solid line. Note that the ordinate of Figure 2 is expressed in terms
of "lumens/sq. meter" which is approximately equivalent to foot-
candles or lumens/ft^2 by divided by 10. Thus, at air mass zero or
outside the earth's atmosphere, the illuminance is about 12,000
lumens/ft^2 and at the earth's surface with an air mass of unity
(sun at the zenith) the value is about 9800 lumens/ft^2.

PROPOSED STANDARD SOLAR IRRADIANCE CURVES (WATTS/m^2/μ), ON A PLANE NORMAL TO THE SUN'S RAYS, OUTSIDE THE EARTH'S ATMOSPHERE (m=0), AND AT THE EARTH'S SURFACE FOR AIR MASSES OF 1, 2, 3, 4, AND 5.

CONDITIONS: ATMOSPHERIC PRESSURE = 760mm
PRECIPITABLE WATER = 20mm
DUST = 300 PARTICLES/cm^3
OZONE = 2.8 mm

R-14,560   REF: J O S A, VOLUME 38, No. 2, FEBRUARY, 1948   FIGURE 1
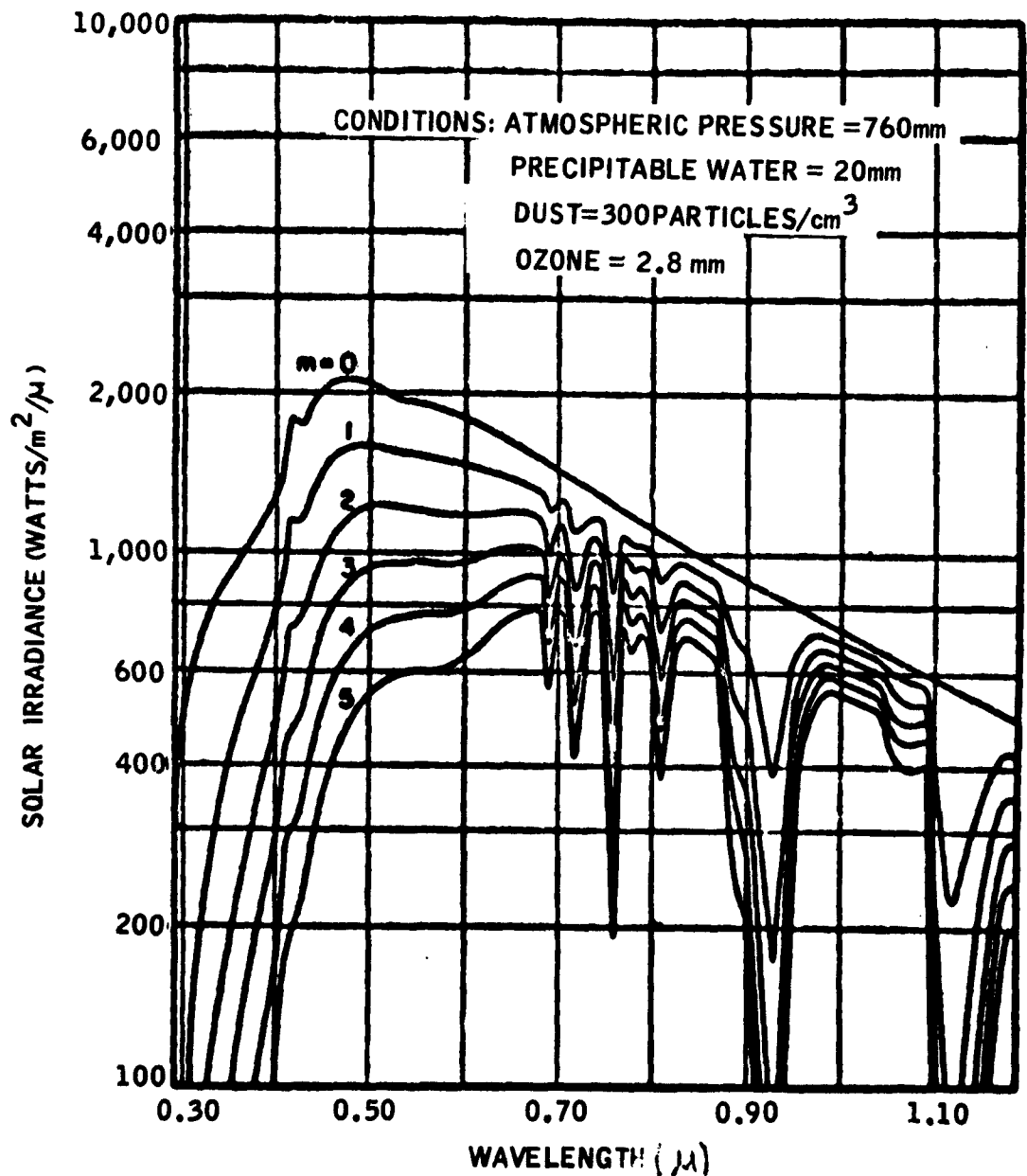
DIRECT SOLAR ILLUMINANCE (LUMENS/m²) AT THE EARTH'S
SURFACE ON A PLANE NORMAL TO THE SUN'S RAYS

REF: JOSA, VOLUME 38, NO. 2, FEBRUARY 1948

R-14,532   FIGURE 2
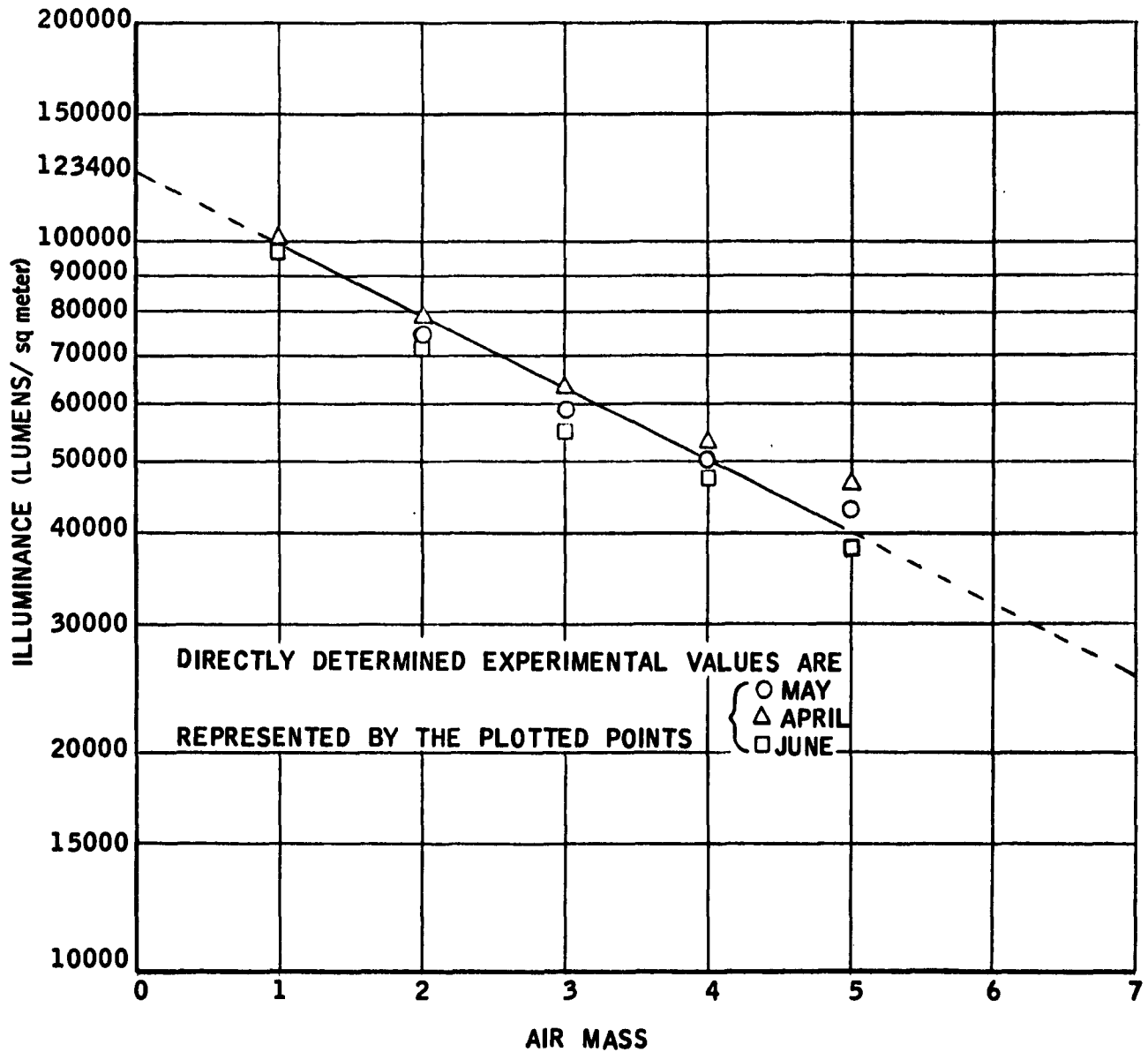
b. Clear Atmosphere Skylight

    Great variability in the skylight conditions
makes a generalized representation of the data much more difficult
than the case of direct sunlight. The most useful set of data
describing the directional aspect of skylight as a time of year is
shown in Table I . The data of Table I show that the sky is far from
uniform in luminance with the maximum values in the direction of the
sun and with the minimum values found about 90° in azimuth from the
sun's direction. Integration of the variable luminance over the
entire sky vault produces the illuminance on a horizontal plane. This
integration process performed numerically for a variety of sky lumi-
nance distributions measured on a world-wide basis results in a range
of curves around the single curve shown in Figure 3. Obviously,
"clear sky" is judged visually in terms of luminance distribution at
various locations (latitudes, propinquity to the sea, and altitude
above sea level). The averaged values of illuminance on a horizontal
plane from a clear sky as shown in Figure 3 are regarded as a suitable
standard for input to various daytime reconnaissance scenes. The total
illuminance of the scene is obtained from the sum of the values pre-
sented in Figures 2 and 3 . For example, the total illuminance of
a horizontal plane on a clear day with sun at the zenith is 9570
lumens/ft^2 (direct sunlight) plus 1480 lumens/ft^2 (skylight) equal
to 11,050 lumens/ft^2. It does not seem probable that the departure
of the values represented in the Figures 2 and 3 from the extreme
conditions termed "clear day" is of sufficient magnitude to be of any
appreciable importance in the relative evaluation of image transducers.

TABLE I

LUMINANCE OF THE CLEAR SKY

WINTER AND SUMMER VALUES

S^1	A^2	2°	15°	30°	45°	60°	75°	90°
0°	0°	319	242	109	60.5	36.3	29.0	25.2
	45	111	120	71.3	49.9	34.3	29.0	
	90	61.2	69.6	52.4	37.0	30.2	27.7	
	135	75.3	86.4	60.7	39.8	29.5	26.0	
	180	96.5	106	69.0	44.6	31.5	27.2	
20°	0°	6140		2550	1110	590	371	261
	45	2330	1450	981	670	457	331	
	90	1030	679	441	339	287	277	
	135	1020	611	371	264	227	230	
	180	1140	666	371	258	211	206	
40°	0°	4190	3450	4780		1380	774	506
	45	2310	1750	1400	1120	891	688	
	90	1330	840	567	506	450	481	
	135	1270	673	415	344	334	380	
	180	1400	729	410	304	293	349	
Clear Sky, Summer								
20°	0°	7850		4040	1510	870	521	372
	45	2870	2190	1450	1020	722	487	
	90	1330	1050	662	502	398	424	
	135	923	692	458	309	268	305	
	180	1060	792	443	316	275	283	
40°	0°	5480	4620	6290		2050	1180	746
	45	3100	2330	2010	1830	1400	1060	
	90	1590	1050	843	724	739	776	
	135	1300	843	552	448	463	552	
	180	1370	828	507	403	395	507	
60°	0°	3180	2660	2820	3840		2520	1530
	45	2660	2340	1990	2340	2560	2160	
	90	1770	1350	1100	1130	1350	1510	
	135	1450	933	719	765	887	1150	
	180	1530	979	719	765	826	1100	
70°	0°	3100	2760	2420	3420	7060		2140
	45	2680	1930	1900	2290	2850	3270	
	90	1650	1390	1200	1160	1330	1900	
	135	1330	899	792	813	942	1410	
	180	1240	835	663	663	877	1310	

1 - Solar altitude
2 - Azimuth from sun

ILLUMINANCE (FOOT-CANDLES) ON THE HORIZONTAL PLANE DUE TO LIGHT FROM THE CLEAR SKY AS A FUNCTION OF SOLAR ALTITUDE.

SOLAR ALTITUDE

REF: JOSA, VOLUME 38, NO. 2, FEBRUARY 1948

R-14,536
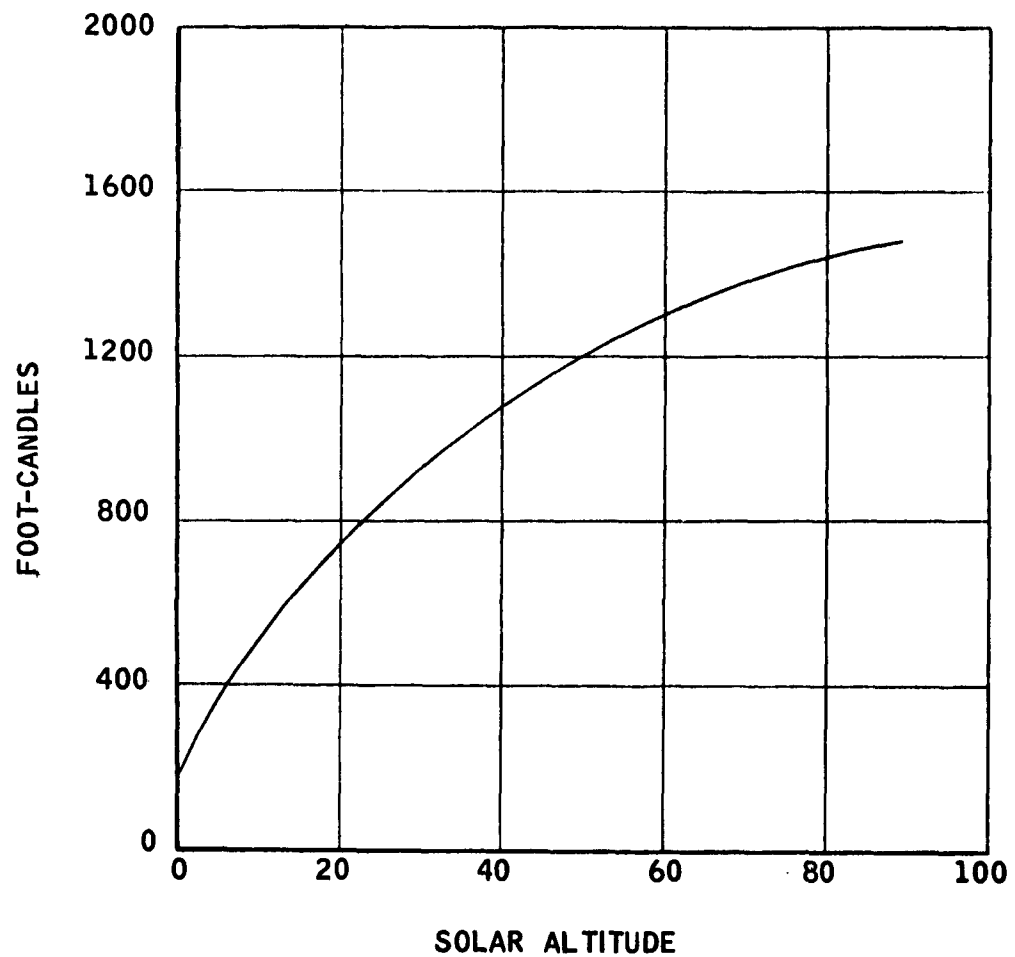
FIGURE 3

c. Total Clear Sky Illuminance on Scene Elements

Thus far only the total illuminance on a
horizontal scene element has been reported as in Figures 2 and 3 .
Scene surface elements in other orientation must also be treated to
establish a realistic range of conditions. Well known relationships
involving solar azimuth and altitude are available to compute the
direct sunlight on planes of various orientations. The clear skylight
on planes of various orientation is obtained by an integration process
that recognizes the distribution of sky luminance as a function of
solar altitude. Normal, perpendicular (facing the sun) and horizontal
planes are selected as representative of typical scene element
orientations. The component illuminances of these various surfaces
are defined as:

I_{n_d} - illuminance on a plane normal (n) to the
sun's rays caused by direct (d) sunlight.

I_{h_d} - illuminance on a horizontal (h) plane
caused by direct (d) sunlight.

Ipd - illuminance of a perpendicular (p)
(facing the sun) plane caused by direct
(d) sunlight.

Ins, Ihs, and Ips - illuminances on the planes
defined above but caused by
skylight (s).

In Figures 4 and 5, the sunlight and skylight
illuminances, respectively, of the three representative planes are
plotted as a function of solar altitude. Suppose, for example, that
the total illuminance at noon on a vertical plane facing south at
Los Angeles, California, on March 31 (clear day conditions) is required
for prediction of the luminance of a reconnaissance scene element.

ILLUMINANCE (FOOT-CANDLES) DUE TO SUNLIGHT (ON
THE NORMAL, HORIZONTAL, AND PERPENDICULAR PLANES)
AS A FUNCTION OF SOLAR ALTITUDE.
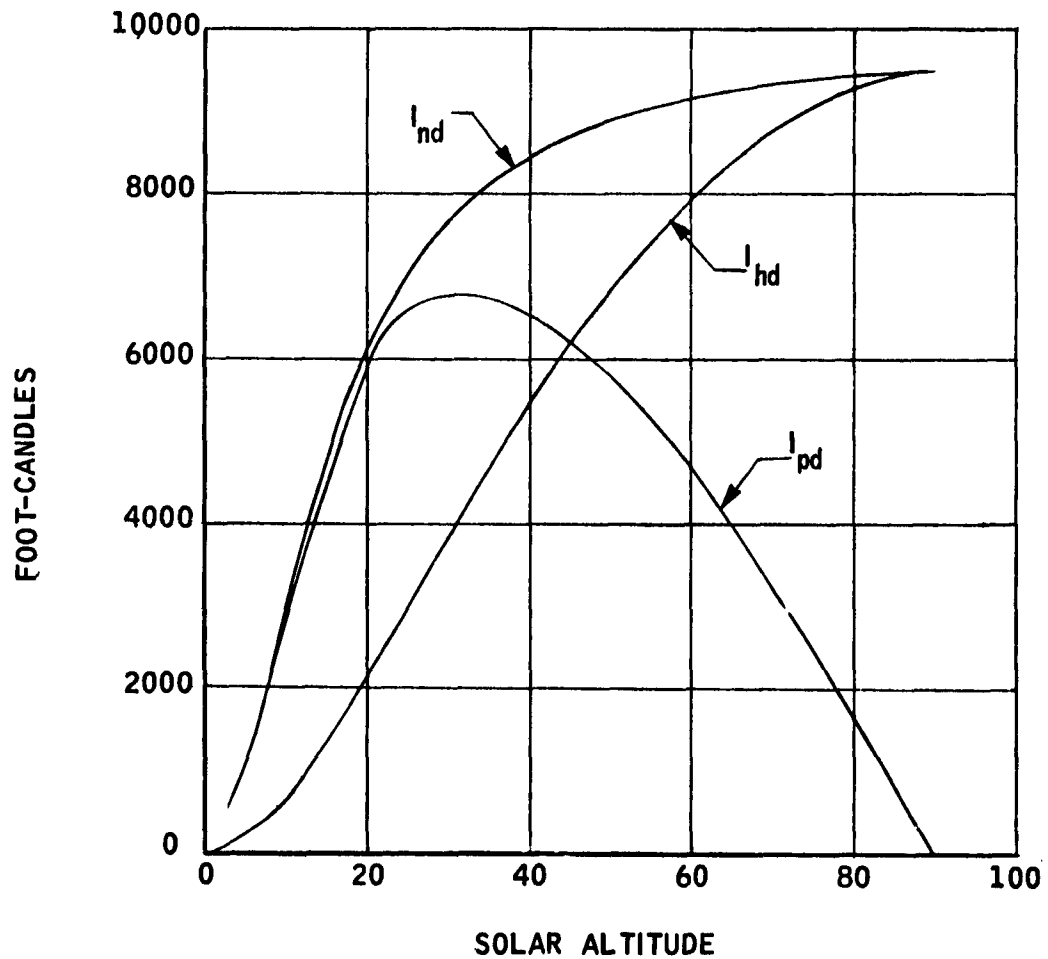
REF: JOSA, VOLUME 38, NO. 2, FEBRUARY 1948

R-14,535

FIGURE 4

ILLUMINANCE (FOOT-CANDLES) DUE TO SKYLIGHT (ON THE NORMAL, HORIZONTAL, AND PERPENDICULAR PLANES) AS A FUNCTION OF SOLAR ALTITUDE.
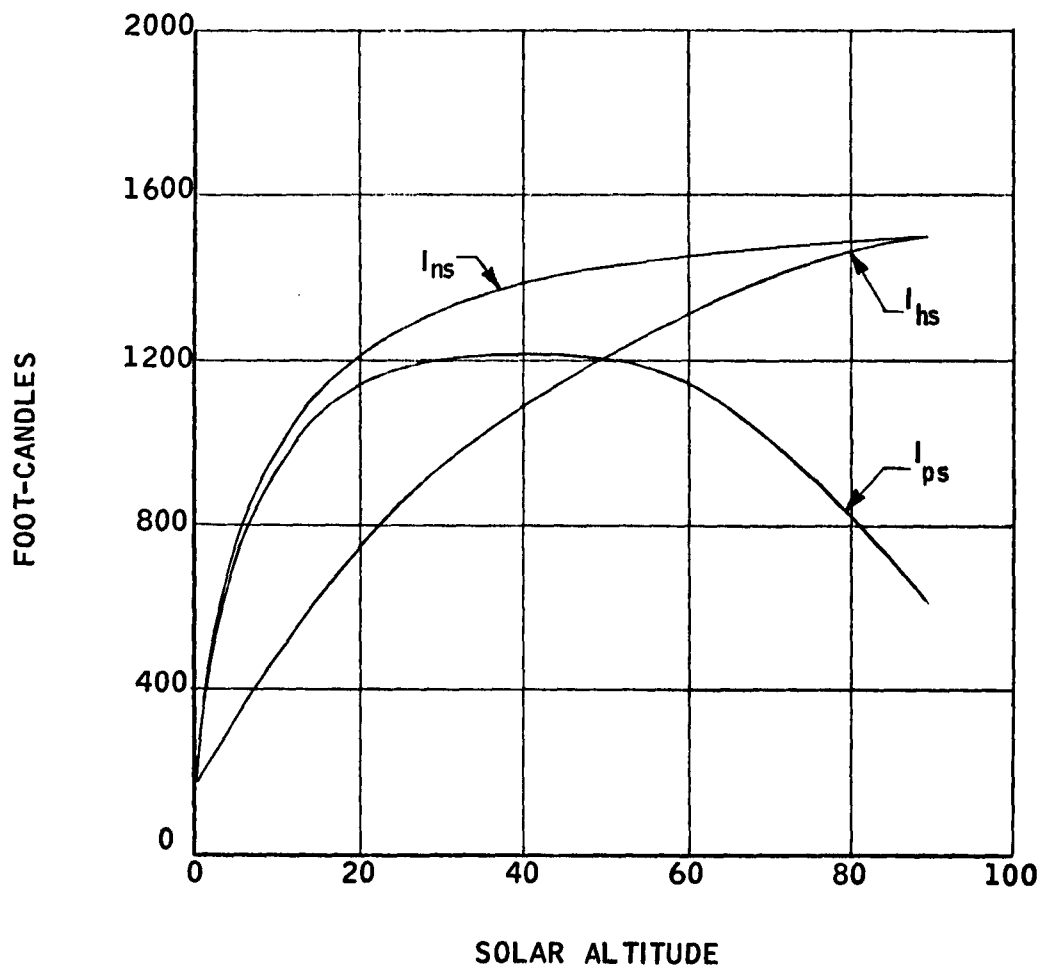
SOLAR ALTITUDE

REF: JOSA, VOLUME 38, NO. 2, FEBRUARY 1948

R-14,534

FIGURE 5

Under these conditions of

        Los Angeles: latitude $= 34°$ North

        March 31:   solar declination $= 0°$

        Noon: solar altitude $= 90°-34°-56°$

the sunlight Ipd is read from Figure 4 and the skylight Ips is read from Figure 5 as follows:

$$Ipd = 5000 \text{ lumens/ft}^2$$
$$Ips = 1150 \text{ lumens/ft}^2$$

The total illumination on the vertical scene element is then the sum of the two component values or 6150 lumens/ft^2.

d. Illuminance Under Non-Clear Atmospheric Conditions

In the preceding sections, the evaluation of the amount of sunlight and skylight available to a scene at the earth's surface has been based on the assumption of an atmospheric condition which, as appraised by visual inspection, is designated as "clear". Such an atmosphere contains no clouds but a small amount of condensed water vapor and some dust. The chief cause of atmospheric non-clarity is the presence of significant amounts of condensed water vapor, clouds, fog, haze, ice crystals and dust which reduce the quantity of lumen flux at the scene and alter its directional characteristics. A range of atmospheric conditions from clear to dense cloud is defined in Table II in terms of the apparent brightness B of the sun and the luminance of the sky as viewed in three representative locations. In a medium haze, for example, the sun's apparent brightness is reduced to one half the value under clear conditions but the position of the sun is still clearly discernable. In addition, the average sky

TABLE II

LUMINANCE VALUES FOR VARIOUS
ATMOSPHERIC CONDITIONS ————— .

Atmospheric Conditions	Sun B		Max.	Sky Luminance foot-lamberts Avg.		Min.
Perfectly clear	500×10^6 450×10^6	(3)	1,400	740	(2)	400
Clear	450×10^6	(1)	6,000	1500	(4)	650
Light Haze	14×10^6	(1)	100,000	4300	(4)	1800
Medium Haze	450×10^3	(1)	25,000	3150		1500
Heavy Haze	15×10^3	(1)	8,000	2150		1200
Light Cloud	0	(1)	4,000	1750		1000
Medium Cloud	0	(2)	2,500	1300	(3)	650
Heavy Cloud	0	(2)	1,200	640	(3)	400
Dense Cloud	0	(2)	400	200	(3)	150

(1) near sun
(2) near zenith
(3) near horizon
(4) approximately 90° from sun, measured through zenith

Note: Numerical values which characterize the atmospheric
       conditions indicated in column 1.

luminance under a medium haze is twice the value under clear conditions
and thus the illuminance Ihs on a horizontal plane from the sky is also
double the clear conditions. Thus the data of Table II allow the easy
evaluation of the luminous input conditions to the scene under various
non-clear atmospheric conditions.

e. **Night Illuminance**

Moonlight and the "lights of the night sky" are
the principal sources of illumination in the absence of sunlight. The
illumination received from the moon depends on the phase angle of the
moon cycle, declination of the moon and sun, and the time of night.
Full moonlight is about 0.01 to 0.04 foot-candles but illumination
from the half-moon is only 10 percent of the full moon value. The
portion of night time during which illumination from the half-moon or
greater is available is about 30 percent. Sun and moon provide an
illuminance greater than 0.002 foot-candles about 75 percent of the
total time. During the remaining 25 percent of the time, illumination
is provided mostly by starlight, zodiacal light (scattered sunlight in
space) and galactic light. The total of these three components of the
lights of the night sky is about 0.00005 foot-candles. The permanent
aurora and the airglow provide an equal or greater illuminance so that
the total lights of the night sky amount to about 10^{-4} foot-candles on
a horizontal plane on a clear night.

2. **Geometric Detail**

The apparent luminance of scene elements represents
the input to the image transducer. This luminance is determined by
the radiant flux (excitation) on the element, the geometrical properties
of the scene, and the spectral reflectance of the scene element. The

significant geometrical detail within the scene and its influence
on the scene luminance is described in this section.

Surfaces of the scene that are directly illuminated
by sunlight or skylight, even if they are relatively low reflectances,
exhibit luminances which are high compared with other surfaces
situated such that they do not receive direct input. Thus directly
illuminated scene elements from the highlights (maximum luminance of
the scene)   are often less significant than the shadowed areas
in terms of the information content (in the reconnaissance sense).
The surface elements of lowest luminance are usually illuminated
either by (a) multiple reflections (interreflections) of sunlight
among adjacent surfaces or (b) light coming from small sky areas seen
through intervening objects of (c) mixtures of (a) and (b) in various
proportions. The illuminance of these darker scene elements is given
by the relationship

$$E \text{ (surfaces + sky, } dA) = F \text{ (}dA, \text{ surfaces) } L_{surfaces} +$$
$$F \text{ (}dA, \text{ sky) } L_{sky}$$

where: E (surfaces + sky, dA) - the illuminance on the
              scene element dA from surfaces in the half space
              with respect to dA and from the small sky area seen.

              F (dA, surfaces) - the total shape modulus or
              configuration factor from the element dA to the
              surfaces.

              F (dA, sky) - shape modulus from the element dA to
              the sky.

$L_{surfaces}$ - total luminous emittance of the surfaces after multiple reflections.

L_{sky} - luminous emittance of the sky.

As an example of the use of the above equation, consider a military vehicle in the shade of several large trees on an overcast (Medium clouds of Table II) day. The vertical surface of the vehicle will see leaf surfaces, ground cover, and some part of the sky. The sky luminance or luminous emittance L_{sky} is read from Table II as 1300 foot-lamberts. A reasonable estimate of the leaf surface emittance $L_{surface}$ is 50 foot-lamberts and with a 10% shape modulus to the sky, the vehicle luminance is

$$E \text{ (tree surfaces + sky, vehicle) } = (0.9 \times 50) + (0.1 \times 1300) = 175 \text{ foot-candles}$$

The amount of luminous flux available to the scene elements of lowest luminance also depends on the spatial distribution and orientation of these elements. That is, some estimate of the mean direction of the normals to the scene elements relative to the direction of view (axis of the image transducer) should be attempted. The scene elements (terrestrial objects) are located at an infinite variety of positions in the three-dimensional space in front of the image transducer. The scene appears to consist of a plane mosaic made up of many two-dimensional elements varying in size and shape, the plane of the mosaic being normal to the line of sight. No predominant orientation of surface elements is found in natural scenes so that it is not productive to select a plane with some particular orientation as being more significant than another plane having one of many possible orientations.

A resume of the geometrical aspects of scene elements is:

   (a)   The illuminance of scene elements in shadowed locations is not related in any simple way to the illuminance of surfaces that see direct sunlight and skylight before multiple reflections.

   (b)   There is little justification for choosing a plane of any particular orientation as representative of the entire natural scene.

   (c)   The integral of all luminous flux incident on the scene without regard to initial direction seems most significant in terms of scene evaluation by the image transducer.

3. Spectral Propoerties of Scene Elements

The study of the spectral emittances of natural scene elements suggests that on the average the spectral characteristics of the flux incident on the element is more significant than the spectral reflectance or transmittance of the material. It should be understood that this condition of effectively gray or neutral reflectances of the scene elements is a correct representation only on the average (the statistical average of a large number of scenes covering the entire gamut of all possible geometrical variations).

In the scene elements (particularly those which receive multiple reflected flux) are postulated to be gray, the spectral composition of the radiant energy reflected or transmitted by these elements is practically identical with that of the incident radiant energy. Because of the multiple reflection process, the radiant energy

incident on the scene elements of minimum luminance is a very
thorough mixture of that present in direct sunlight with that of the
radiant energy coming from the entire sky hemisphere. The mixture
proportion of the two components is approximately the same as the
ratio of the two fluxes incident on a horizontal plane.

The spectral composition of the radiant energies
reaching the earth in various phases of sunlight and skylight will
now be considered. In Figure 6 , the solid Line A is the specto-
radiometric emission curve for the international photographic unit
of intensity. The dashed curve B represents the spectral composi-
tion of annual mean noon sunlight with a clear atmosphere at
latitude 40° N.

Mean noon sunlight on clear days at latitude 40°
has been assigned a color temperature of 5400°K, but color tempera-
ture is an index of the visual appearance of light and not of a
physical characteristic such as spectral distribution. Experience
with the detailed analysis of the relative capabilities of non-
gray image transducer responses suggests that color temperature is
not a useful measure of the spectral composition of the radiant
energy.

The mixture of direct sunlight and skylight on
a horizontal plane on a clear day is depicted by Curve D in
Figure 6 . Curve C of the same figure represents the spectral
composition of the radiant energy on a horizontal plane under a
completely overcast sky (heavy cloud condition of Table II).

Radiant data that define the physical basis of
scene composition are reported and discussed in this section.

SPECTRAL COMPOSITION AT VARIOUS RADIANT ENERGIES

CURVE A -- SPECTRAL COMPOSITION OF RADIANT ENERGY EMITTED BY THE INTERNATIONAL PHOTO-GRAPHIC UNIT OF INTENSITY.

CURVE B -- SPECTRAL COMPOSITION OF RADIANT ENERGY IN MEAN NOON SUNLIGHT AT LATITUDE 40° (CLEAR ATMOSPHERE).

CURVE C C' - SPECTRAL COMPOSITION OF THE ENERGY FROM COMPLETELY OVERCAST SKY; DOTTED PORTION EXTRAPOLATED.

CURVE D - - SPECTRAL COMPOSITION OF RADIANT ENERGY REFLECTED FROM A NON-SELECTIVELY ABSORBING HORIZONTAL PLANE ILLUMINATED BY SUNLIGHT AND SKYLIGHT (CLEAR ATMOSPHERE).

WAVE-LENGTH, mμ

RELATIVE ENERGY

REF: JOSA, VOLUME 39, NO. 2, FEBRUARY 1949

FIGURE 6

R-14,531

Representative values of direct sunlight, skylight, total illuminance,
and night illuminance are presented as the necessary input to any
scene evaluation approach. In addition, the importance of geometric
detail and spectral properties of scene elements are discussed. The
data of this section used in conjunction with the scene categorization
method reported in the First Quarterly Progress Report allow the com-
plete specification of representative scenes. The response of a
variety of image transducing systems to these representative scenes
is related to the broad objectives of this study.

Some specific conclusions to be drawn from this
section are:

(a) A standard set of curves describing the spectral
distribution of direct sunlight to scene elements
as a function of atmosphere path length (air mass)
is available (Figure 1).

(b) The total illuminance on the outdoor scene under
clear conditions is obtained as the sum of the
data for sunlight (Figure 2) and skylight
(Figure 3).

(c) Luminous conditions associated with the extremes
of atmospheres designated as "clear" do not
depart from the average value (Figures 2 and 3)
enough to be of any appreciable importance in
the relative evaluation of image transducers.

(d) Direct and skylight illuminances on normal,
perpendicular (facing the sun) and horizontal
scene elements can be obtained from Figures 4
and 5 .

(e) The data of Table II allow the evaluation of
the luminous excitation of the active scene
under various non-clear atmospheric conditions.

(f) The illuminance of scene elements in shadowed
locations is not simply related to the illumi-
nance of surfaces in direct sunlight because of
the multiple reflection process that conveys flux
to the shadows is described by a complicated
integral equation.

(g) A useful and reasonable postulate is that scene
elements, on the average, are effectively gray
in reflectance and transmittance so that the
spectral character of the flux streaming from
the scene element toward the transducer is
identical to the spectral distribution of the
illuminant.

4. Scene Categorization

          The data of the preceding sections used in conjunc-
tion with the scene categorization method reported in the First Quarterly
Progress Report allow the complete specification of many representative
scenes. It has been pointed out that the geometry, excitation, and
spectral properties of scenes are extremely complicated. In view of
this, a complete classification of all scenes into specific groups and
subsequent establishment of the image transducer parameters for these
groups is beyond the scope of this present study.

          The important point to note is that the study does
present a scene evaluation approach. This approach coupled with the
data presented with the study of similar data can be utilized to define
the image transducer parameters for a specific transducer mission.

For example, consider the case of specifying the image transducer parameters for a low level (i.e., altitude) drone reconnaissance mission under daylight conditions. Luminance characteristics of 126 outdoor scenes * under daylight conditions which are applicable to the drone mission are given in Table III.

126 scenes have been categorized into the four geometry groups discussed earlier, plus a fifth group. Excitation conditions for each of these four groups varied but in most cases consisted of the excitation categories described in E-3 through E-6. Also included in Table III is a fifth group of scenes consisting of a combination of scenes from groups G-1 through G-4 where the excitation was a low illuminance large area diffuse source.

Table III shows the average and extreme values of the maximum and minimum luminance for each group of scenes. In addition, the maximum, minimum, and average luminance ranges for each scene in both arithmetic and log units are given. The logarithmetric form of expressing luminance range is included since it offers a convenient means of discussing tonal reproduction. A study of the table shows that the average for the minimum luminance decreases progressively in the first four groups. The average maximum luminance behaves in the same fashion but decreases at a slower rate. The luminance range increases for the first four groups. In the section at the bottom of the table under "Summary of All Scenes" are given the averages applying to all 126 scenes.

- -

* Jones, L.A. and Condit, H.R., "Scene Structure, Directional Index, Photographic Efficiency of Daylight, Safety Factors, and Evaluation of Camera Exposure", J. Opt. Soc. Am., 39 (1949).

TABLE   III

LUMINANCE CHARACTERISTICS OF 126 OUTDOOR
SCENES UNDER DAYLIGHT CONDITIONS

	*Minimum Luminance B Min	*Maximum Luminance B Max	Luminance Range Log	Luminance Range Arithmetic	Detectable Tonal States (Based on .05 Density Step)
(1) Group G-1	- Distant Scenes - 28 Scenes				
Min.	20	1500	1.43	27	24
Max.	160	11500	2.45	285	49
Avg.	55	4500	1.90	81	38
(2) Group G-2	- Semidistant Scenes - 30 Scenes				
Min.	8.4	820	1.54	35	31
Max.	76	9200	2.53	340	50
Avg.	24.5	3150	2.11	130	42
(3) Group G-3	- Near Scenes - 38 Scenes				
Min.	5.6	620	1.62	42	32
Max.	31.0	8000	2.79	620	56
Avg.	12.5	2400	2.27	190	45
(4) Group G-4	- Close Up Scenes - 19 Scenes				
Min.	2.0	710	2.06	115	41
Max.	11.6	4000	2.87	750	56
Avg.	4.6	1600	2.53	345	50
(5) Combination of Groups G-1 to G-4 Under Low Level Diffuse Excitation - 22 Scenes					
Min.	.82	55	1.43	27	28
Max.	50.0	3700	2.80	640	56
Avg.	6.3	1050	2.21	165	44
Summary of All Scenes - 126 Scenes					
Min.	0.82	55	1.43	27	28
Max.	160.0	11500	2.87	750	57
Avg.	14.5	2300	2.20	160	44

*   Luminance Values are in Foot Lamberts.

It is apparent from these data that on the average the minimum
luminance is 14.5 foot-lamberts, the maximum luminance is 2300 foot-
lamberts giving the average luminance scale of 160.

The foregoing conditions represent the complete range
of luminance that an image transducer would be expected to encounter
on a drone type mission. From these data, parameters such as number
of detectable tonal states, sensor sensitivity, resolution and similar
parameters can be determined. For example, the number of detectable
tonal steps based on a .05 density step assumption is shown in Table III.
On the average, the transducer would be expected to resolve 44 tonal
states as indicated.

C. IMAGE TRANSDUCING PARAMETERS - AN IMAGE TRANSDUCER SURVEY

1. General

As pointed out in the First Quarterly Progress Report
the study of image transducing parameters had progressed to the point
of defining five parameters characterizing the performance of image
transducing and deriving a parametric expression interrelating these
parameters. In addition, initial ranges were established for the para-
meters based on theoretical considerations. It was indicated that a
logical continuation of the parameter study would encompass the
following items:

(1) Establish practical ranges for the several parameters
     based on practical transducer limitations such as
     granularity, noise, and so forth.

(2) Develop a suitable method for displaying the infor-
     mation content of the parametric expression interrelating
     the parameters.

(3) Obtain a more comprehensive picture of the relative
     importance of the parameters as a function of transducer
     mission in order that parameter trade-off possibilities
     can be delineated.

(4) Establish the desired performance parameters of an
     advanced image transducer and translate these into the
     appropriate design criteria.

During the past Quarter Period this study has
continued in the light of the above objectives. In particular, Items
(1) and (3) above have received the major emphasis by the conduction
and completion of a cursory survey of the present state-of-the-art of

image transducers. This survey briefly summarizes the characteristics
of image transducer systems and discusses the interrelation of the
various parameters from a practical viewpoint.

        The results of this survey coupled with a continued
effort which has taken place during this quarter on the objectives
mentioned in (2) and (4) above should bring an effective conclusion
to this study during the third quarter.

        Although work has been accomplished in all defined
areas of the study, only the image transducer survey is included as
part of this report.

        For the most part, these developments have been
clustered around the Television and Graphic Arts or Film industries
since these industries today represent the largest markets. However,
in recent years, military and industrial requirements have demanded
an extension of image transducer parametric limits - more sensitivity
in pickup tubes - greater speed or capacity in graphic art or image
processing, or recording - more environmental restrictions (12, 17)*.
There has been a correspondingly large outcropping of new devices
to meet these special requirements. New devices are ruggedized,
have new spectral ranges (ultraviolet, infrared), very low sensi-
tivities, much higher resolution, different frame or scan times, are
lighter in weight, simpler and more reliable. Other potentially
interesting storage, display, and transducing devices are also under
development which, in many applications, may replace or supplement
the use of the very versatile conventional image tube transducers.

* Numbers in parenthesis refer to references in Section II E.

A brief review of image storage and transducer
devices, their component limitations and parametric tradeoffs are
described in the following pages. Section IV contains a graphical
summary of the more significant image transducer devices, their
salient parameters and their theoretical limits.

2. Image Transducer Types

a. The Iconoscope (35)

The iconoscope is an early pickup tube develop-
ment. It has largely been replaced in use by the image orthicon
(which is more than 100 times more sensitive) or the vidicon, which
is simpler. However, the iconoscope is still useful when high
definition and good storage properties are desired and sensitivity
is not too important.

The iconoscope uses a photo-emissive surface
constructed in an electrically isolated mosaic pattern. Light from
a scene projected on this photo-sensitive surface emits electrons.
The electrons accumulate at each image point during the frame time.
Once, during each frame, a high velocity electron beam scans over
this mosaic surface restoring the charge to its original value. A
capacitive pickup senses the current flow to a wire mesh adjacent
to the mosaic surface.

The beam electrons rarely require energies
in excess of 1000 electron volts. Beam currents are typically .1 to
.5 micro-amperes.

The sensitivity of an iconoscope, can, in
principle, be increased by image amplification. Image iconoscopes.

have been built which enhance the stored charge on the mosaic target
by using secondary emission multiplication of the electrons emitted
by a photoemissive cathode. The photo electrons are refocused by
an electron lens onto the target element which provides multiple
secondary emissions. The remaining signal detection process of
the image iconoscope is similar to the ordinary iconoscope.

Typical examples of the image iconoscope
include the Multicon, Superemitron, Eriscope.

b. The Orthicon (35, 36)

The orthicon, in contrast to the iconoscope
uses a low velocity scanning beam. The electron beam is slowed by
a decelerator just before reaching the target. The beam current may
typically be .02 micro-ampere. The scanning beam is reflected from
the target by the presence of a stored charge on the first mesh
screen. The amount of reflection provides signal indication.

The electron emission from the target is
collected on an adjacent wire mesh. This emission leaves the target
at a positive potential. The scanning beam neutralizes the target
charge and returns it to its original potential. The number of
electrons repelled by the charge is amplified by a secondary emission
electron multiplier in the base of the orithicon tube.

The commonly used photo-emissive surface and
target provide a sensitivity gain of 5 in electron emission. The
secondary emission multiplier is typically a five stage device which

introduces negligible noise compared to that generated by the scanning electron beam (shot noise).

Typical examples of the image orthicon are the type 7198 and the 5820. New developments have included the use of a more sensitive S-20 tri-alkali photo-cathode and high resistivity thin film target (e.g. Westinghouse's WL22722). Larger area photocathodes have also recently been reintroduced (4-½ vs. 3" tube) (2,12). The thin film target provides an increase of 10-15 times and the S-20 photo-cathode 5 times in sensitivity over conventional image orthicons.

Image intensifier sections have also been added to these tubes to provide more than 1 stage electron image amplification before integration on the target (25d, h). Typical development tubes are RCA's C73477, C74093A and Westinghouse's WX4299. The intensifier section increases sensitivity by as much as 10 to 20 times. In combination with an S-20 surface and thin film target, new image intensifier orthicons are 500 to 1000 times more sensitive than image orthicons of a few years ago. The image intensifier orthicon is the most sensitive of any image transducer today.

c. The Isocon (35c)

Shot noise in the returned scanning beam is the principle limitation of the normal orthicon. At low light levels, essentially the entire beam is returned. It is precisely at these low light levels that random shot noise in the returned beam is greatest (i.e. the noise is greatest when the signal is weakest (6, 25)).

The isocon tends to provide the smallest shot noise when the signal is weakest. The detection principle involves the use of the scattered electrons which do penetrate to the target, and hence, there will be a small returned beam current when the scene or signal is the darkest. The electron beam shot noise is greatest when the signal is greatest.

The principal problem in the development of this tube has been the separation of returned electrons from scattered electrons. Nonetheless, this development potentially offers greater sensitivity, and signal to noise, at low threshold signals than other transducers.

The developmental RCA C74060 is an image intensifier isocon (25d). The use of image intensifier stages ahead of conventional image orthicon permits a sufficient charge buildup in the target itself that the signal will override its own beam noise at low signal levels.

d. The Vidicon (35, 36)

The foregoing devices use a photoemissive cathode. Light striking a photocathode emits electrons which are then amplified through secondary emission multiplication and finally collected and refocused in a stored charge pattern on a target. The electrostatic charge pattern is then read from the target by a scanning electron beam.

Another photon to electrical characteristic phenomena is one of photo conductivity. A photon, incident upon a photoconductor, forms charge carriers at a rate proportional to the

incident light intensity. If the photoconductor is located in a
bridge circuit with a constant potential balance, the change in
free carriers will change the current through this photoconductor.
The change can be detected in the bridge.

The vidicon uses a photoconductive target.
The target has, on one side, a conductive coating, (high resistance
R) and a dielectric substrate (which acts as a capacitor C).
Initially, the capacitor is charged to a fixed potential, which
then leaks off, due to the presence of the RC combination, at a
rate proportional to the illumination. One side of the glass, or
MgO, acts as a capacitor charged to a fixed potential. At the
readout time, the capacitor is partly discharged. The amount of
electrical charge imparted to each element by the electron scanning
beam is then detected at the conductive coating itself through a
video amplifier.

The vidicon is a very simple device. It is
small and light weight. Typical tubes include 6326 or 6198.

Recent developments include larger photocathode
surfaces (3/5 x 4/5 inches vs. standard 1/2 x 3/8 inches, RCA 8051),
the use of higher resistivity thin film targets for longer time
constants (Westinghouse 7290 which employs longer integration and
slow scans), and new photoconductive surfaces with different spectral
characteristics favoring long wavelength radiation thus being more
sensitive to 2870°K tungsten source illuminated scenes (Westinghouse
4915). The vidicon attains the largest tonal range or signal-to-
noise ratio of any other imaging device (approximately 200:1).

e. The Ebicon (36, 37)

          The ebicon is a modified form of vidicon which
uses an image section. A photoemissive cathode emits electrons which
are then refocused on a photoconductive surface. The target is a
thin electron permeable aluminum layer on a high resistance semi-
conductor. The bombarding electrons induce conductivity in a thin
film of selenium. The remainder of the Ebicon tube operates as a
conventional vidicon. Another version, The Uvicon operates on the
Ebicon principle but uses an ultra violet photoemissive cathode.

f. Thermoplastic Recording (3, 4, 23)

          Thermoplastic recording utilizes a reusable
storage and recording process. The film consists of a heat resistant
base film coated with a thin film of thermoplastic material which is
readily deformed by heat. An electron beam images an electrical
charge pattern on the film. Heat is then applied to the film.
The thermoplastic material melts, and electrical and electrostatic
forces deform the thermoplastic film -- the displacement is a function
of the charge interaction and the surface tension of the film. The
film is cooled and the data stored. For reuse, the film is reheated
to the melting point of the thermoplastic material.

          Thermoplastic recording was developed by
General Electric in recent years. The electrical time constant must
be 50 to 100 times the thermal time constant. For example, if 1/2
second is used for exposure, 1/2 minute is needed for cooling.
The cooling technique presents the greatest problem. Presumably
thermoplastic material has an ASA 10 equivalent photo speed, can
record 40 lines/mm, and 8 shades of gray. It is expected to attain

100 lines/mm resolution, a tonal range 15 shades of gray, and attain a
recording density of 1.5 x 10^7 elements/square inch. As a reusable
device, it has the longest storage time ability of any other sensing
material.

g. Phototape (11)

Phototape is another recent development in
reusable image storage. This technique has been developed by Radio
Corporation of America. A transparent polystyrene base has overlaid
on it a transparent thin gold conducting layer, a photoconductor, and
a dielectric insulator. With simultaneous image exposure and
electronic beam contact across this film, a charge pattern is
introduced on the insulator proportional to the light intensity.
The charge may be stored for several days. Readout is accomplished
by an electron beam readout in a manner analogous to the readout of
the vidicon.

Resolution of the tape is expected to approach
1200 lines/mm. However, electron beam spot size presently limits this
to 40 lines/mm on a 2-¼ inch format. Normal gray scale rendition
of 8 to 10 levels has been obtained. The readout is, at present,
only partially destructive, but usable pictures can still be
obtained after 2 or 3 readouts. Phototape has the highest resolution
of any other short term non-destructive, storage mechanism.

h. Film (19, 38)

Film has, for many years, enjoyed widespread
use for high quality recording of high density data. Automatic
film processing, however, is messy. The film is radiation-sensitive

and, in the past, has not been reusable. Basic film resolution is
quite high. Poor film resolution occurs occasionally due to camera
or shutter motion, or the film not being flattened against the plates.

Present films obtain 150 lines/mm resolution with
ASA 3 ratings (bright targets) or 25 lines/mm with weak targets (ASA
650). The quantum efficiency of the film is high, basic film reso-
lution being limited ultimately by the clumping of silver halide
grains.

Present developments favor the use of vacuum
evaporated monomolecular silver bromide and single crystal silver
bromide. These developments may lead to 200-300 lines/mm resolution
with reusable, radiation resistant film having an ASA rating 10-25.
Film has the highest resolution and tonal range of any other recording
or storage medium.

i. Image Intensifiers and Image Converters (14, 25
    a,b,c,i, 27, 30, 31, 33, 34)

Many image intensifier and image converters
employ a photo-emissive cathode surface, an accelerating electron
multiplication, and a phosphor target which emits radiant energy
when struck by electrons. The phosphor radiant image is in general,
more intense than the image focused on the photocathode. A light
amplification factor of many hundred is possible. Image intensifiers
have recently been used on the front end of image orthicons for
improved sensitivity.

Image intensifiers operate continuously. Their
integration time is solely a function of the build up and decay time

of the phosphor. Electrons incident upon a phosphor area excite certain
phosphors. If more electrons impinge, more phosphors will be excited
and the spot size will, in poor resolution systems, appear brighter
until saturation occurs. This accumulation or reciprocity effect
is not exact and exists only over times which are short compared
to the decay time of the phosphor and are well below the saturation
current of the phosphor.

Two types of image intensifiers currently
under development are Westinghouse's transmission secondary emission
intensifier (TSEM with accelerating dynodes and RCA's two or three
stage cascaded electrostatically or magnetically focused image tube.
Other solid state image intensifiers are also under development.
These intensifiers combine electroluminescent layers with photo-
conductive layers to form imaging panels.

j. Storage Tubes (26)

There are many types of image and scan con-
version tubes which store different tonal or gray levels at each
image point. The tubes generally employ charge restoration or some
form of charge modulation.

Most of the tubes have separate read and write
guns -- and may have three or four guns. (Two read, one erase, and
one write gun, etc.). Readout may occur at nominal television
frequencies (i.e., 1/30 second --) or the picture may be stored
for minutes or hours before readout (generally with some image
quality degradation). Tonal range is a problem. In storage devices
which retain information up to 5 minutes, 8 to 10 gray scale is

possible. For the longer time storage tubes (hours or days) almost
all gray scale information is lost.

    The charge restoration tubes include the
storage orthicon (photoemissive) CBS emitron; a Grapherhon (electron
bombardment induced conductivity); VCR X 350; a Metrechon; numerous
direct view storage tubes such as Westinghouse's 7268, 7356, 7682,
WX 4584, and RCA's C73922, 31, 38, 59, 83, or 6866, Dumont's
Storatron, ITT's Iatron, Hughes' Tonotron and Memotron. A vidicon
type storage tube, the Permachon; uses charge modulation. It is a
direct pickup storage device (5 min.). There are several scan con-
version tubes which readin information at one rate and pattern and
readout at different rates, Intercontinental Electronics Corporation
TMA-403X, RCA's barrier grid-storage Radechon (also ITT), or Intec's
TCM-154.

  k. <u>Flying Spot Scanner (No Integration)</u>

    Historically speaking, mechanical flying spot
scanners antedate all of the foregoing image storing and scanning
techniques. A very large number of devices have been built, invented
and discussed. All such devices suffer from the same limitation;
lack of integration of light during the frame time.

    The Nipkow scanning disk is an early example.
A number of mirror drum devices have also been built. Most facsimile
and wire photo equipment use the sequential readout, non-integration
type mechanical scan. Examples of this are the Electronic Communi-
cation, Standard Products Division facsimile equipment used by Western
Union, the Westrex <u>FAXWRITER</u> or <u>PRESSFAX</u> (with a 16" x 22" format used
for the Stewart Warner's DATAFAX used widely by the telephone company,
and Fairchild Camera's continuous strip recorder.

Infrared scanning and reconnaissance devices
have also used strip scanning with mirror or drum rotation at high
speeds. Haller, Raymond and Brown's AAD 2 or AAR 2 (Reconofax),
and Texas Instruments' line scanner are recent developments.

The above scanners, by and large, use a fixed
photo sensitive cell and some image, mirror, lens or drum rotation
mechanism. Another way of obtaining line scan motion is by use of
electronic deflecting plates in a photomultiplier type imaging tube.
Such a device was developed by Farnsworth (ITT) and is known as an
Image Dissector. Again, as in all of these flying spot scanning
devices, no integration is performed. Also, scan motion can be
obtained electronically without requiring the use of moving
mechanisms.

3. Mechanical Scanning Sensor and Recording System

Mechanical scanners employ (1) a physically
moving scanning mechanism, (2) an optical condenser or projection
system, and (3) a photon sensitive detector for image to electrical
transducers, or a light source and modulator for electrical to image
transducing. The scanning mechanism most often consists of a rotating
disk or drum upon which (1) optical imaging rays are deflected in a
predetermined way, (2) upon which a series of limiting field stop
apertures are sequentially brought into use, or (3) upon which the
picture itself is brought past a stationary pinhole and sensor or
light source.

The frequencies or time rate with which information
is gathered is an important parameter for measuring the inherent
capacity of the overall system. If the bandwidth is large, then the

intermediate electrical transmission system must have adequate capacity
to handle this wide band information. Facsimile systems for example,
have, until recently, limited their communication system to telephone
lines. This results in a low frequency ($\approx$200 cps) data rate. More
recently, however, due to the greater availability of radio and
microwave links, newer systems have been and are being developed with
much greater capacity. Stewart Warner has a new 10 KC bandwidth
system for example, Westrex has just recently introduced a 47 KC
bandwidth system capable of 300 scan/min (400 lines/in. resolution)
and before the end of the year hopes to bring out a 935 KC system
with 3000 scan/min. Fairchild Camera, Facsimile Division, also
has some new wide bandwidth systems in development that may shortly
be brought out.

The higher frequencies require sensors that can
respond at this rate, and lights or light modulators that can record
at his rate. The sensor is not a problem. Photomultiplier and
photo-emissive detectors have bandwidths comparable to 10^8 cps.
Conventional TV pickup devices normally operate at 4.5×10^6 cps
and could, in principle, approach the bandwidths of a photomultiplier
tube.

Light modulators at these frequencies present more
of a problem. Glow lamps for the most part have been used in the low
frequency bandwidth system. The intensity of the light source has
been directly controlled by varying the exciter current through the
tube. Frequencies to 10 or 20 KC are perfectly feasible with this
technique. At much higher frequencies some recent developments, such
as the GaAs infrared source, may prove to open a much broader range
to the direct modulation of source illumination.

High frequency light modulators have most often used
an intermediate attenuating or polarizing material. The Kerr cell is
a prime example. A beam of polarized light, passing through a
birefringent material is affected by the direction of the incident
light. The incident polarized light is broken into two components,
which traverse the medium at different velocities dependent on the
material, and the applied voltage on the material -- an organic liquid.

Another light modulation technique is that of
diffraction, which scatters light. The diffraction phenomena arises
when supersonic waves are introduced into some liquid by a piezo
electric crystal. This technique has been used in recording systems
for some years by Fairchild Camera.

The transmission of wideband frequencies without
distortion introduces problems in the fidelity of reproduction. It
is necessary that the recording system be synchronized with the
transmitting system. This takes the form of a synchronizing signal
between receiving and transmitting stations. Even so, the relative
"flatness" of the frequency bandwidth, and delay distortion are problems
which may vary slightly with different frequencies.

Some of these difficulties can be overcome by use
of frequency or pulse code modulation in the transmitting system
(instead of more conventional amplitude modulation (39)). Frequency
modulation is substantially unaffected by small variations in
relative amplitude of the transmission band -- and hence the band-
width need not be flat (to $\pm$ 2 db as is frequently cited).

Pulse code modulation or digital systems obtain
the same objective. Here, in addition, the amplitude, or tone level

of the transmitted signal can be encoded in bits to reduce the needed
bandwidth. The pulses so transmitted each occupy the entire band
and lack of distortion or uniformity of response across this band
is unimportant. (42,43).

The mechanical scan methods are very numerous.
The Nipkow disc, a series of perforated holes on a disc -- all
stepped down in progressively smaller radii, can, in one rotation
sweep out a number of lines in an image equal to the number of holes
in the disk. This scan mechanism is extremely simple. However, it
requires an extended light source which encompasses the whole field.

Another mechanism employs a series of mirrors on
a drum, each mirror serving to deflect the converging beam from a
light source down another line, and the rotation of the drum sweeping
the projected light across the width of the image.

Another technique uses a large stationary drum
with many mirrors and a small rotating mirror in the center which
progressively employs each separate external mirror.

Another common technique is to fix the light source
or sensor, but instead rotate the copy. A synchronous motor drives
the drum at the line scan frequency, and a geared down translating
mechanism drives the pickup, recording lamp, or drum itself slowly
in a direction normal to the rotation of the drum.

Table IV following, lists a few of the facsimile
recording and transmitting equipments which are currently available.
They each individually possess some unique feature or advantage in
certain applications. The Western Union TELEX or WIREFAX for example,

TABLE IV

SOME TYPICAL FACSIMILE EQUIPMENT

TRADE NAME	MANUFACTURER	COPY SIZE	Transmission Time in/min.	Resolution Lines/inch	SCANS/MIN.	BANDWIDTH	CARRIER	Signal Contrast
FAXWRITER	Westrex	8.5" x 13"	1.86	96	180	1.2-3.6 KC	2.4 KC	16 db
1. PRESSFAX	"	16" x 22"		400	300	47 KC		25 db
2. PRESSFAX(Wall St.)	"	16" x 22"		800	3000	935 KC		25 db
AN/GXC-4 (XC-2)	"	4-3/16" x 3¼"	0.40	300	120			30 db
(70 mm cont. on RCR with Polaroid Film)	"		0.80	300	140			30 db
AN/GXC-5	"	8½" x 11"	12.5(12 min)	96	90	.5-5 KC		20 db
"	"	"	25 (6 min)	96	180			20 db
WEATHERFAX	"	18" x 36"		96	60		1.8 KC	15 db
"	"		(29 min)	96	90	.6-4.2 KC	2.4 KC	15 db
"	"			96	120		2.4 KC	15 db
CF/RF Photofacsimile	"	8" x 11"	(11 min)	96	90	1.2-2.4 KC	1.8 KC	
DATAFAX	Stewart Warner	8½" x any	1.875	96	180	1.2-2.4 KC	2.4 KC	
DATAFAX	"	"	3.75	96	360	.3-2.3 KC	4.5 KC	
3. DATAFAX					900	10 KC		
SCANAFAX	Fairchild	8½" x any	(3-6 min)	100	180-360	1-2.7 KC	2.4 KC	27 db
INTRAFAX	Western Union	8½" x 11"	(3-6 min)	100	180-360		Voice	20 db
ELECTRONIC MESSENGER	"	8½" x 14"	(1-2 min)	85	180-360	.8-4.1 KC	3.6 KC	20 db

NOTE: 1,2 and 3 to be introduced in near future.

is reputedly better adapted to the transmission line type delays and
distortion occurring over long transcontinental transmissions,
Westrex has some high capacity developments, (47 KC and 935 KC which
will soon be out) and have further reduced to military form and
field use, some equipments which are adaptable to transmission
of Polaroid 3 x 4 in. snapshots, AN/GXC-4 (XC-2), or larger copy
AN/GXC-5. This latter development advantageously employs FM modula-
tion in contrast to most other equipments in use.

Stewart Warner, DATAFAX and Fairchild Camera both
have facsimile devices which can use copy of any length on a roll
but of limited width (8-1/2 or 11 in.). Westrex has a PRESSFAX and
WEATHERFAX which can transmit large width copy; 16" x 22" and 18" x
36" respectively.

4. Component Limitations and Parametric Tradeoffs

a. Photon Noise Limits (10, 18, 29, 35, 38)

Ultimately, photon noise always limits the
performance of any image sensor or transducer. Photons are little
packets of discrete energy equal to $h\nu$, where h is Planck's constant,
and ν is the frequency of oscillation (c/λ). Near the visible
spectrum, the wavelength λ, is short, and the photon energy is
large. The emission, and reception of photon energy in discrete
units must be considered at low light levels or at high data rates.
There must be at least one photon received in a discrete area during
a given detection interval to provide indication of intelligence.

Photons are neither emitted nor received at a
constant rate. There is a statistical fluctuation of individual quanta.

The distribution is Poissonian. Thus, if an average of 1 quanta is received per unit time, the probability of actually receiving a photon in a particular time interval is only 68%. If the average rate of arrival is 5 quanta per unit time, then there is better than a 99% probability that at least one quanta will be received in any particular time interval.

A random arrival of photons introduces unpredictable noise. With the arrival of large numbers of photons in a bandwidth limited system, the noise fluctuation is found to vary with the square root of the number of photons arriving in a unit time (the law of large numbers). If an average of 100 photons are present, there will be a 10% ripple.

The photon noise limit can be simply calculated. The number of photons received per resolution element in one frame or integration period from an ambient intensity is:

$$\overline{M_a} = \eta_o \, N_B \; n \, A_i \, T_F \, (f/\#)^{-2} = H_a \, n \, A_c T_F \, \left[\overline{N}(f/\#)\right]^{-2} \eta_o$$

and the number of photons from a change in average intensity (contrast) focused on a single resolution element is:

$$\overline{M_s} = H_s \, nA_o \, T_F \, \eta_o$$

where:

$\overline{M_a}$ = number of average background photons

$\overline{M_s}$ = number of average signal photons

N_B = background radiance watts/cm^2 steradian (at entrance aperture)

H_s = signal irradiance watts/cm^2 (at entrance aperture)

n = watts to photon/sec conversion factor (1/hν)

A_o = optical collector area in cm^2

A_i = area of resolution element on photocathode A_c/N^2 in cm^2

A_c = area of photocathode on sensor in cm^2

N = resolution (lines across photocathode)

T_F = research or integration frame, in seconds

$f/\#$ = optical speed in f numbers

η_o = optical efficiency (1-losses)

A photoemissive surface does not emit an electron with every incident photon. It has a quantum efficiency, η_q, which is a measure of the average number of received photons necessary to emit one electron. Typically the quantum efficiency may be 10 to 20% for some surfaces (see following sections). The signal to noise then becomes:

$$(S/N)_{theor} = \frac{M_s \eta_q}{(M_a \eta_q)^{1/2}}$$

$$(S/N)_{theor} = \frac{(f/\#)H_s A_o N(\eta_o \eta_q n T_F)^{1/2}}{(N_B A_c)^{1/2}}$$

(see conditions below)

This signal to noise is only a theoretical
ratio. In a real system, one must also impose the additional
constraint that at least 1 photon be received, (although 5 is a more
realistic figure).

$$M_s \eta_q \geq 1$$

$$H_s n A_o T_F \eta_o \eta_q = 1$$

If one wishes to determine tonal range exactly,
then photon noise in the limit is contributed by signal irradiance,
H_s itself. In these circumstances the signal becomes ΔH_s instead
of H_s and the uncertainty, or photon noise from this background N_B
must include H_s itself. The S/N can be increased by:

1) Larger Collector area A_o
2) Greater resolution N
3) Longer integration time T_F
4) Slower optics (but this reduces capacity of the system)
5) Smaller photocathode area A_c (but this reduces capacity of the system)
6) Better optical or quantum efficiencies η_o, η_q
7) Brighter illumination $H_s/(N_B)^{1/2}$

If the limit on performance is the arrival of
a single photon, then this can be obtained only with:

1) Larger optical collecting area A_o
2) Longer integration time T_F
3) Better optical or quantum efficiencies $\eta_o \eta_q$
4) Brighter object irradiance H_s

b. <u>Spectral Sensitivity</u>

       The spectral selectivity and quantum efficiencies
of presently known photo-emissive, photoconductive, and photo-chemical
transducers vary over very wide limits. Figure 7 shows the spectral
sensitivity of typical emissive surfaces.

       Most optical sensor characteristics are measured,
for convenience, in foot-candles against a 2870°K standard tungsten
source. This is an unfortunate choice for a source unless one is
using the sensor with this type of illumination. Thus, long wave-
length spectral sensitivity may look apparently like a "more sensitive"
photocathode in 2870°K light. (This is the case of S-20 photocathode
now widely used in the more sensitive image orthicon -- or the newer
"sensitive" vidicon). However the quantum efficiency may be no
better than shorter wavelength sensors, and, if short wavelength
illumination is used (solar illuminated, moonlight, or arc or plasma
lamps), then these apparently more sensitive sensors may, in operation,
be no more sensitive than shorter wavelength sensitive sensors with
poorer apparent 2870°K luminous sensitivity. (An S-5 or S-17 surface
may be better under these conditions than an S-20 although the S-20
can quote a lower luminous sensitivity).

       There are 621 lumens/watt of monochromatic .556
micron radiation. Integrating the number of lumens in a 2870°K source
and comparing it with total black body radiation, the luminous effi-
ciency is:

$$\frac{\int K_\lambda F_\lambda (2870°K) \ d\lambda}{\int F_\lambda (2870°K) \ d\lambda} \ = \ \frac{9.75 \ w/cm^2}{400 \ w/cm^2} \ = \ 2.4\%$$

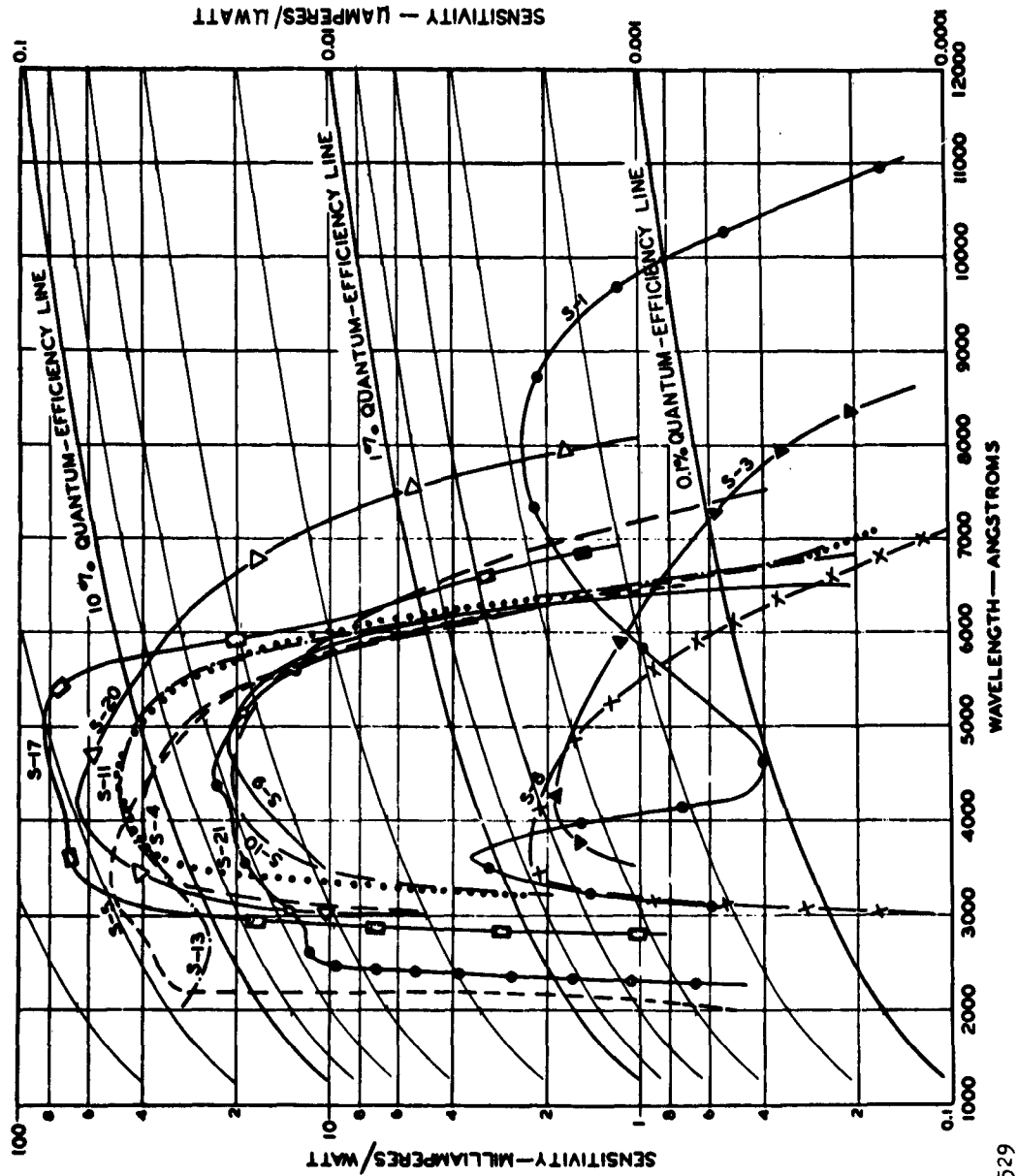SPECTRAL RESPONSE CHARACTERISTICS OF TYPICAL EMISSIVE SURFACES

FIGURE 7

R-14,529

where;

K_λ = The relative spectral response characteristics
of the eye (dimensionless)

F_λ = Spectral radiation characteristics of the 2870°K
source (watts per unit area per unit wave length)

The luminous efficiency in lumens/watt is

$$\text{Luminous Efficiency } 2870° \text{ L source} = \frac{9.75 \times 621}{400} = 15 \text{ lumens/watt } (2870°K)$$

An S-20 tri-alkali surface represents one of
the most sensitive photocathodes presently available. The total per-
centage of 2870°K radiation sensed by an S-20 surface is:

$$\frac{\int_\lambda K_{S-20} \, F_\lambda \, (2870°K) d\lambda}{\int_\lambda F_\lambda \, (2870°K) \, d\lambda} = \frac{18.6}{400} = 4.65\%$$

or, the number of lumens per watt sensed by the S-20 surface.

$$\frac{\int K_\lambda F_\lambda \, (2870°K) \, d\lambda}{\int K_{S-20} \, F_\lambda \, (2870°K) \, d\lambda} = \frac{9.65 \times 621}{18.6} = 322 \text{ lumens/S-20 watt of 2870°K}$$

The luminosity response of the S-20 is 150
microamps/lumen. A conventional image orthicon (5820 or 6849) has a
response of 36.6 microamps/lumen, a sensitivity of .0173 amps/watt
or a luminous conversion of 2870°K radiation equal to 473 lumens/watt.
The standard vidicon (6826 for example) has a response of 520 lumen/watt.

An experimental long wavelength sensitive vidicon
developed by Westinghouse (WX4915) has a much lower instability threshold.

$$\frac{\int K_v F_\lambda (2870°K) \, d\lambda}{\int F_\lambda (2870°K) \, d\lambda} = \frac{21.2}{400} = 5.3\%$$

WX4815 vidicon   = 330 lumen/watt

c. <u>Resolution (5, 7, 8, 9, 13, 12, 18, 38)</u>

Resolution is affected by many factors. A
periodicity of line number is often used as a measure of the apparent
resolution. This is a repetitive pattern, of equally spaced black
and white bars called a space frequency response.

The resolution limit is the periodicity which
is just barely detectable. Thus, if a target has initial high
contrast (i.e., with large signal to noise factor) the resolution
limit occurs with minimum detectable signal (i.e., a very low signal
to noise factor). The signal has been subjected to a very large
attenuation factor, and only very bright targets can be detected at
this maximum resolution limit.

Figure 8 shows the space frequency response
characteristic of a typical tube. The attenuation characteristic
of a tube is a measure of signal attenuation at a particular line
frequency. Sometimes an "effective" line number is used, N_e, which
occurs when the response just equals in intensity the square wave
input at one point.

The space frequency response characteristics of
an image transducer are dependent on several factors. These are:

SPACE FREQUENCY RESPONSE CHARACTERISTICS
OF TYPICAL IMAGE TRANSDUCING TUBES

OBJECT TEST PATTERN	IMAGE RESPONSE	RATIO a/b
"IDEAL" RESOLUTION	b	a	$a/b = 1$ $(a/b)_{fund.}$
EFFECTIVE RESOLUTION	b	a	$a/b = 1$ $(a/b)_{fund.}$
THRESHOLD RESOLUTION	b	a	$a/b \ll 1$

"HIGH RESOLUTION" VIDICON

IMAGE ORTHICON 0° C

VIDICON

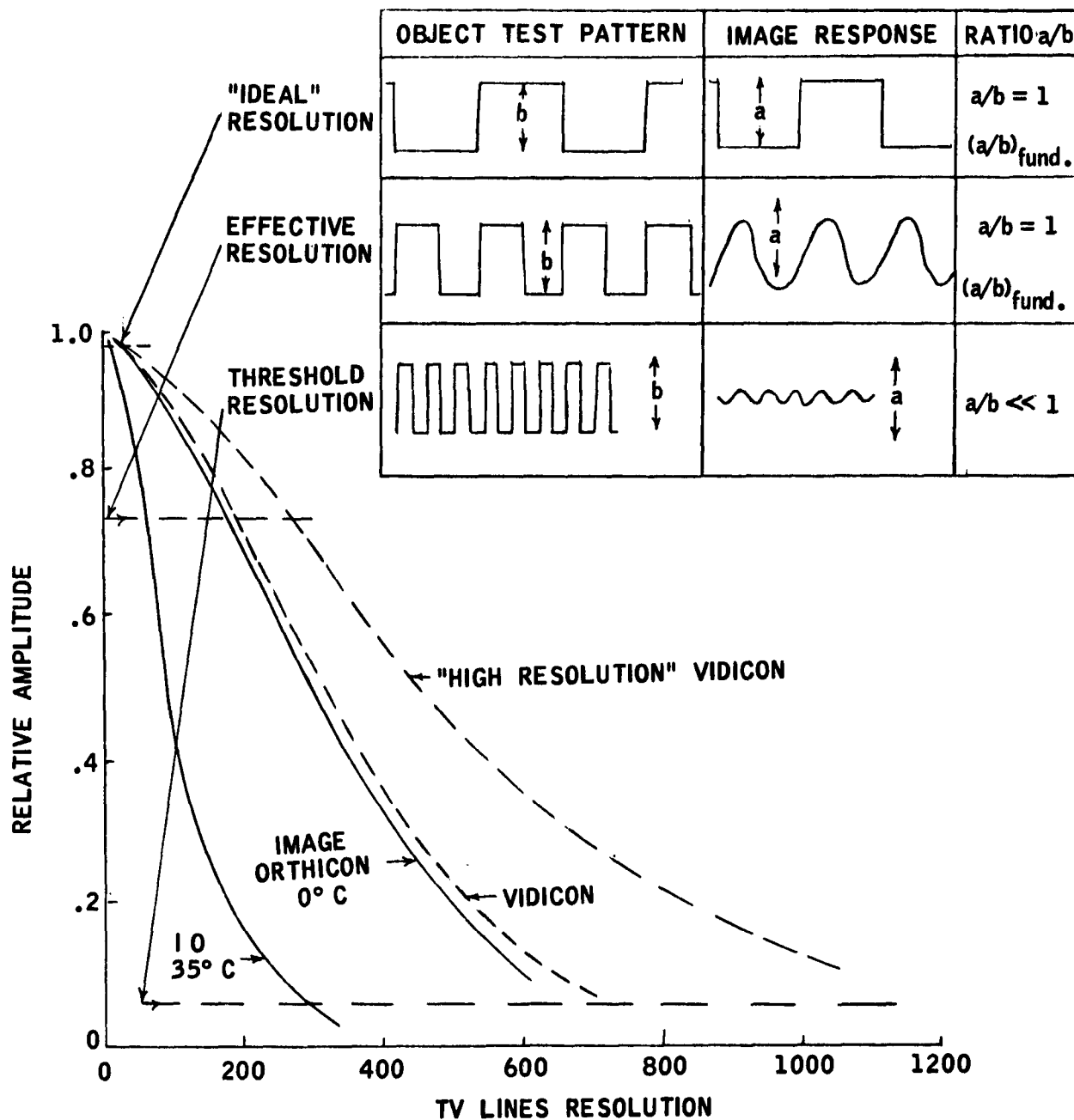I O 35° C

RELATIVE AMPLITUDE

TV LINES RESOLUTION

FIGURE 8

R-14,563

1) The diffraction limit of the collector.

2) Aberrations and imperfections in the imaging lens.

3) Granularity in the photo sensitive surface -- grain
   sizes may be 10 microns or smaller -- however clumping
   and side scattering diffuses effective spots to 100
   microns or so.

4) Lateral charge leakage in the target of integration
   type sensors (Vidicon, Orthicon) due to insufficiently
   high resistivity or small interelectrode capacitance.

5) Imperfect electrostatic or magnetic focusing.

6) Velocity differences in scanning electron beams
   emitted by filament.

7) Velocity differences in photo emitted electrons due
   to differences in incident photon energy occurring with
   non-monochromatic spectral source radiances.

Figure 9, for example, shows the degradation
in resolution due to finite leakage with target thickness of .0002
inches, target mesh spacing of .002 inches and target glass resis-
tivity of 10 ohm-cm. for various integration times (36). Figure 10
shows the theoretical resolution due to velocity differences (i.e.,
Item 7 above) which might be obtained in a target as a function of
the upper wavelength cutoff of source illumination. This latter
figure assumes an upper wavelength cutoff at 7000 Å of an S-10
surface, where the photon energy of 7000 Å is just able to overcome
the work function of the photo emissive cathode.

d. Granularity

The projection, recording, or display of an
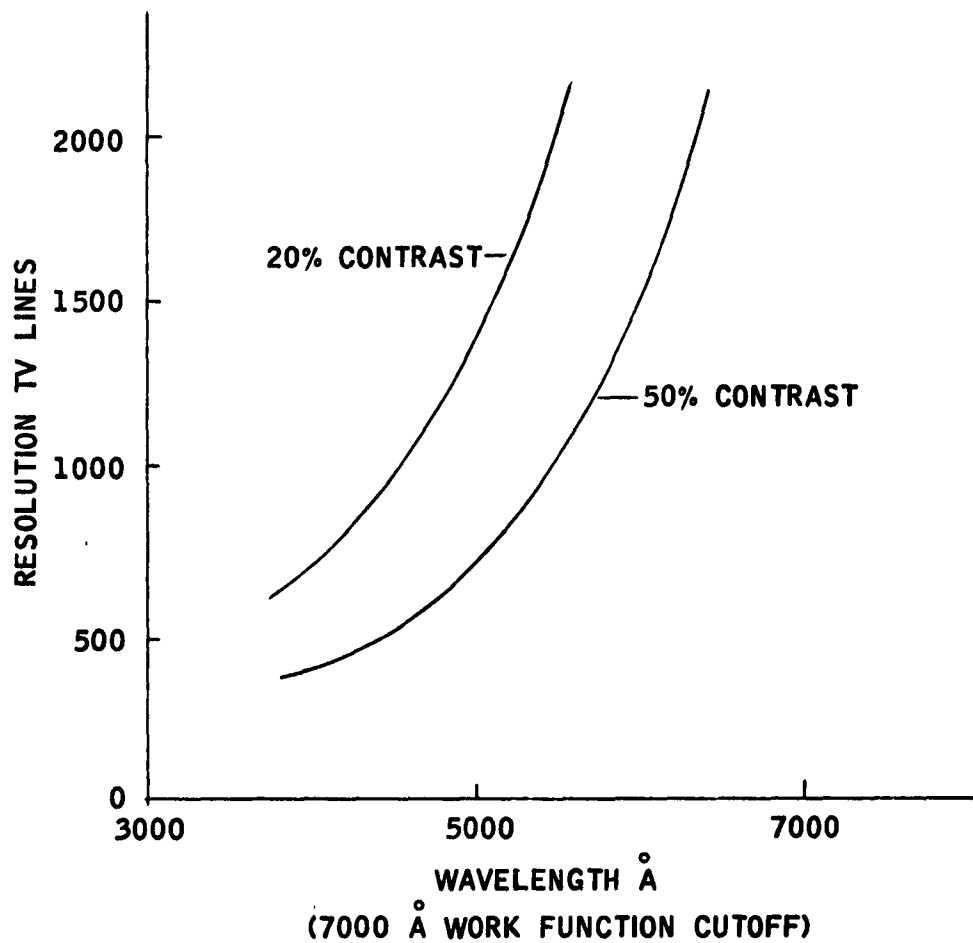image is ultimately limited by the granularity of the surface itself.

DEGRADATION OF RESOLUTION DUE TO LATERAL CHARGE LEAKAGE FOR A SPECIFIC TARGET AS A FUNCTION OF INTEGRATION TIME
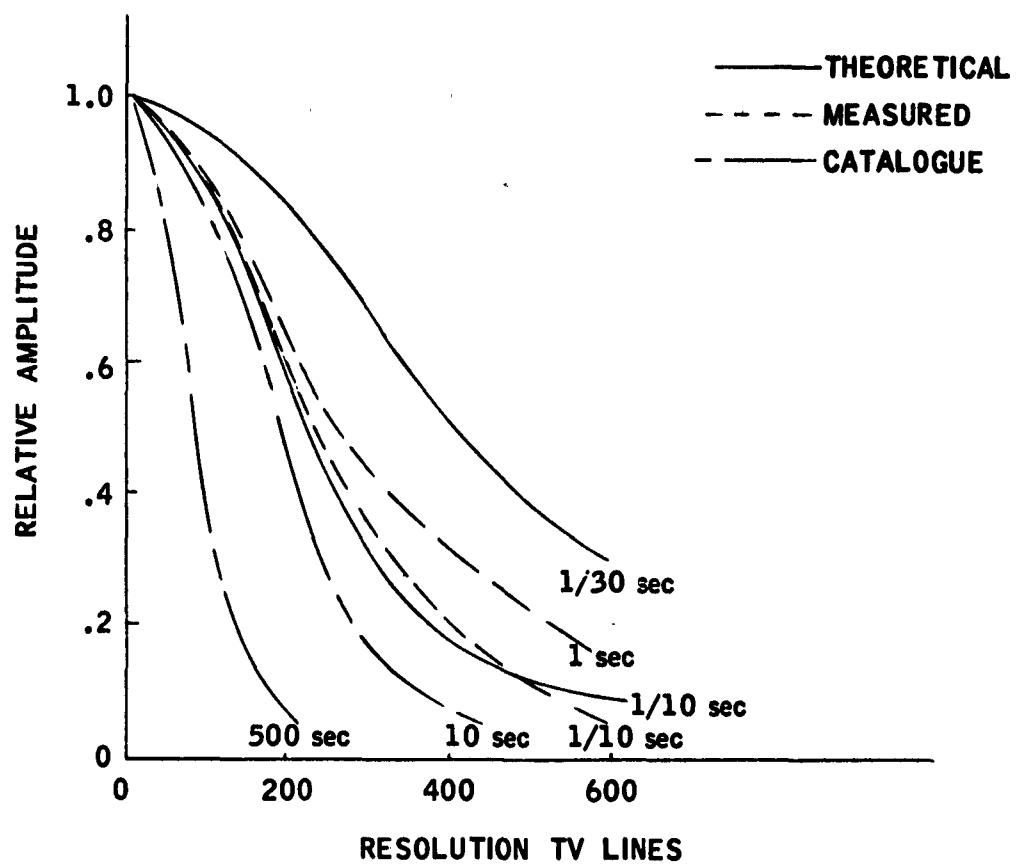
R-14,566

FIGURE 9

THEORETICAL VARIATION OF RESOLUTION WITH WAVELENGTH
WHICH MIGHT BE OBTAINED IN A TARGET

R-14,565

FIGURE 10

Photographic emulsionsfor example, have grain sizes of 10 to 40
microns for high sensitivity film -- which may be reduced to only a
few microns with film having poorer sensitivity. Assuming a typical
grain size of 20 microns, then a film size of 1.6 inches is required
to record 2000 lines. In addition to the basic grain size there is
another phenomena which degrades resolution -- clumping. This is
the characteristic behavior of grains to show more affinity to
other grains then to stand alone.

An image orthicon has even larger minimum
resolution. It is of the order of 80μ. Thus, a 6" photocathode
would be necessary to record 2000 lines if there were no other
deteriorating effects such as the difference in wavelength dispersion
discussed earlier. An image intensifier orthicon with an additional
accelerating-electron lens, source of "spread", obtains typically
100μ and an 8" photocathode would be necessary. These photo-
cathode areas are much larger than have been developed to date.

Simply increasing the size of the scanned areas
alone does not necessarily increase the resolution. Beam spread,
electronic or magnetic focusing and velocity differences in
electron emission, all tend to increase proportionately with image
transducer size.

That some improvement in resolution can be
obtained with larger size tubes however is attested to by the
development of the RCA 8051 Vidicon, which has obtained a threshold
1200 line resolution and uses a 3/5 x 4/5 inch photocathode (22).
It has a 60% response at 400 lines resolution. This compares with
conventional Vidicons having a 1/2 x 3/8 inch photocathode which

obtains only 700 to 750 line resolution and whose response at 400
lines is only 30%. Similarly Marconi Wireless Telegraph Co. rein-
troduced the 4-1/2 inch image orthicon in Europe in 1958 and RCA in
the U. S. in 1960. These tubes obtain better resolution than the
more widely used 3 inch image orthicons (2, 12, 24, 40). RCA's
tubes are the 7295 and 7389. At 400 lines resolution, for example,
their response is 60% instead of the more conventional 40 or 50%
of 3 inch image orthicons.

Large diameter Kinescopes are also able
to attain 2000 to 3000 line resolution which is better than that
obtained by the ordinary pickup tubes or smaller display devices.

There are techniques for reducing the granu-
larity effect and thereby improving resolution. A striking example
of this is the work by Dr. Feldman at N. R. L. (41). Phosphors
were evaporated upon a transparent substrate and then refired to
reintroduce certain contaminants lost in the evaporation process.
The result was a much thinner layer of phosphor. In addition, the
heavy scattering normally associated with Fresnel reflections
from particulate matter is missing. Very high contrast and
resolution was obtained by this technique with very little halo
or ghost effect (certain films also have antihalation coatings
and RCA's 7293A has an antighost). A similar technique is under
development for high resolution film using evaporated monomolecular
silver bromide and single crystal silver bromide.

e. Integration Time (7, 9, 25)

If long integration times are allowed the
transducer has more time in which to collect photons. For this

condition the lateral charge leakages of the targets described above
must be reduced in order to attain a better sensitivity. This
reduction may be accomplished by specially designed high resistivity
thin film targets or by cooling the tube to increase the surface
resistivity of the target (i. c., decrease the free electron
mobility).

Figure 11, for example, shows the improved
response of some standard type image tubes when scanned at slower
scanning rates. The threshold is noticeably lowered with longer
frame times (25h). Some tubes have been specially designed with
thin film, high resistivity targets for slow scan operations. The
Westinghouse 7290 and WX 4384 Vidicons and the WL22724 (or 22723,
22722) image orthicon are examples.

Slow scan rates and long integration mean,
of course, that rapidly changing scenes, or target motion cannot
be readily resolved. The blurring effects of image motion with
slow scan speeds are described in Reference 8 and 25h.

5. Graphical and Tabular Summary

Some of the more salient features and typical
characteristics of image transducers in existence today are set
forth in tabular and graphical form immediately following. The
data have been gathered from manufacturer's articles and numerous
technical papers. Data have been extrapolated where necessary to
form some sort of comparative norm. As such, the data cannot be
regarded as final, but only indicate present limits of difficulty

RESPONSE CHARACTERISTICS OF SOME STANDARD IMAGE
TUBES AS A FUNCTION OF SCAN RATE

IMAGE ORTHICON

PHOTOCATHODE ILLUMIN (foot-candles)

5820

6474

VERTICAL SCAN RATES (frames/sec)
(FOR S/N = 10)

VIDICON

PHOTOCATHODE ILLUMIN (foot-candles)

TUBE B

TUBE A

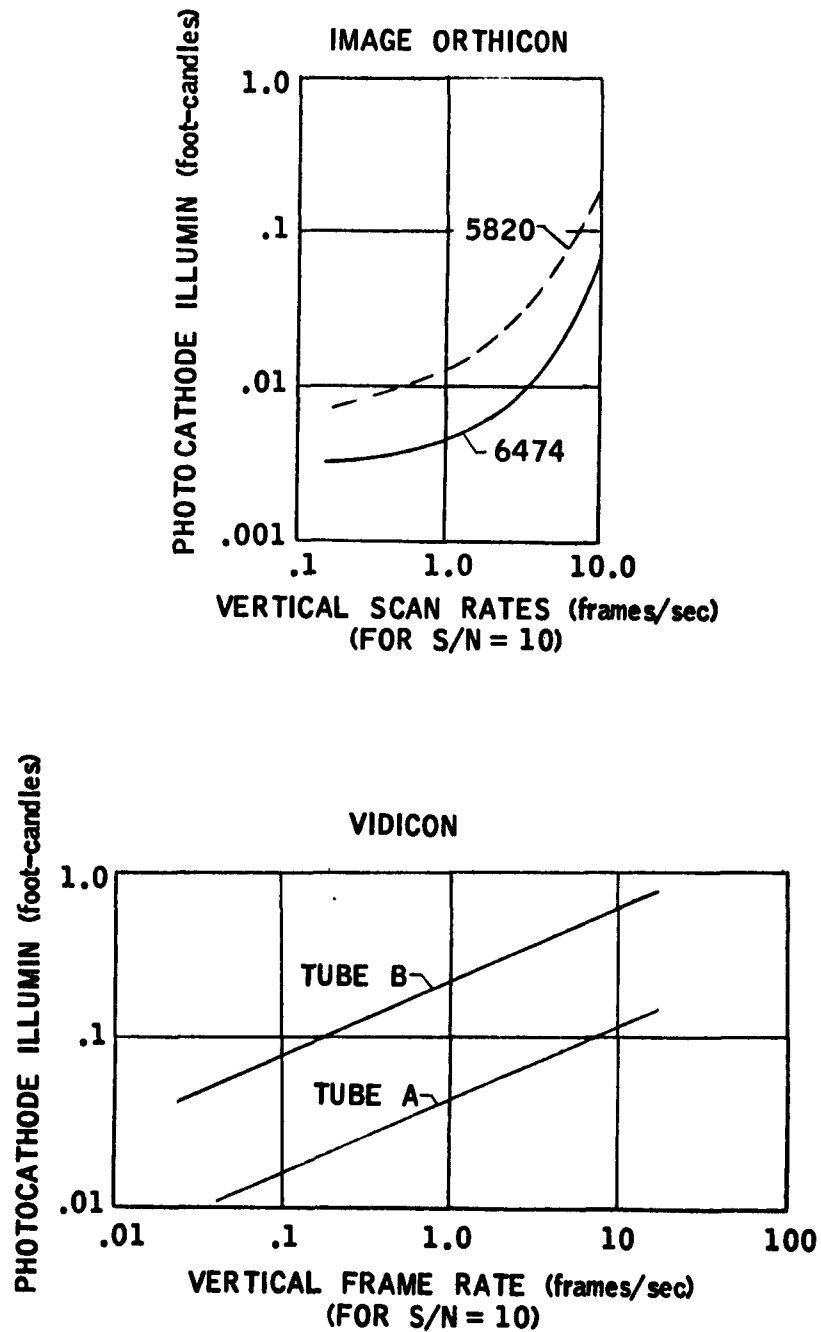VERTICAL FRAME RATE (frames/sec)
(FOR S/N = 10)

FIGURE 11

R-14,564

and trends beyond which substantial development effort is necessary
to extend the limits of these particular devices.

In many instances, the performance limits or
parameters quoted are for the limiting or maximum value assuming all
other parameters are optimized. Actually, the parameters interact
with each other so that a limit on one value will not occur with a
limit on another. This is particularly true of signal to noise
ratio (S/N) resolution, sensitivity, and scan time. Wherever possible,
the interactions are noted.

An examination of all existing transducers covers
a wide range of physical principles. Moreover, it is difficult to
establish meaningful parameters which can serve as a common denomi-
nator for a basis of comparison. For example, with a cathode ray
type image transducer, resolution is commonly expressed as "number
of TV lines". This expression is a complicated function of such
items as bandwidth, line scan spot size ratio, and vertical linearity
of the specific deflection circuits. An indication of resolution for
silver halide film, on the other hand, is more specifically related
to the media itself and would be expressed in "lines per millimeter".
In the graphical presentations that follow, the parameters and units
have been chosen to conveniently express relationships and do not
conform, in all cases, to common usage.

Figure 12   presents the relationship between the
resolution of an image transducer and time. The independent variable
of time spans the interval necessary for exposure, processing,
storage, and readout. In this fashion, the ranges of operation of
existing transducers are related.

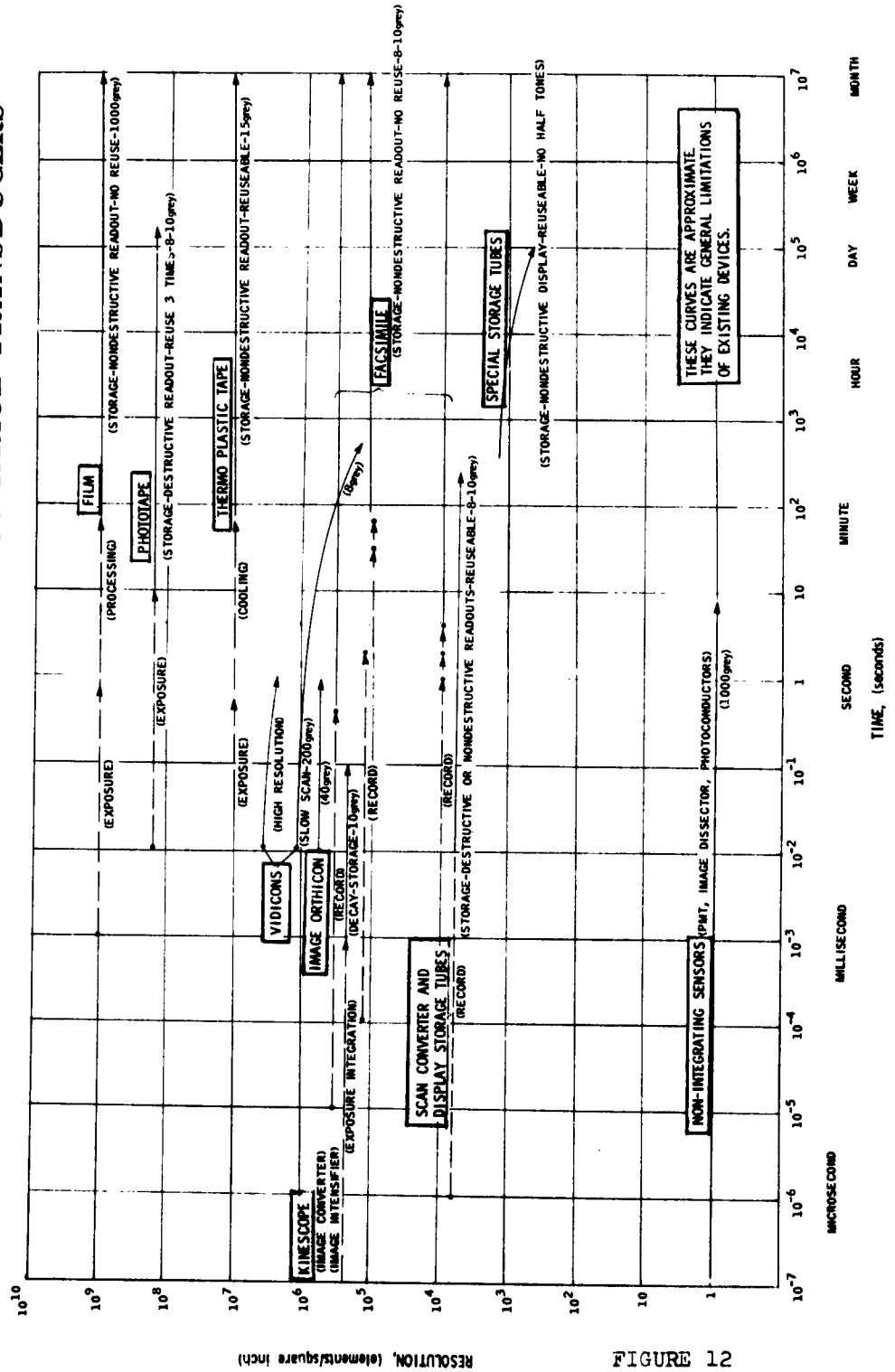SALIENT CHARACTERISTICS OF VARIOUS IMAGE TRANSDUCERS

FIGURE 12

In Figure 13 resolution is shown as a function of photo cathode irradiance. This graph is intended to show how this relationship, for representative transducers, compares with the theoretical limit.

Figure 14 describes the variation of the signal to noise ratio photo cathode irradiance. A comparison between representative image transducers is possible.

The variation of necessary integration time for minimum detection as a function of signal irradiance is shown in Figure 15 . This function for various transducers can be compared with the theoretical limit.

The above material is intended as background material; it is intended to characterize the range of certain transducer parameters for comparison only. The ideal transducer (or the proposed transducer) cannot be related within such a frame of reference at this point in the study program. The ideal transducer must be more specifically defined by its physical properties before a full correlation can have meaning. However, the graphical summaries do serve the purpose of classifying the range of limitations of existing image transducer systems.

RESOLUTION AS A FUNCTION OF PHOTOCATHODE ILLUMINATION FOR SEVERAL SENSORS

FIGURE 13

R-14,554
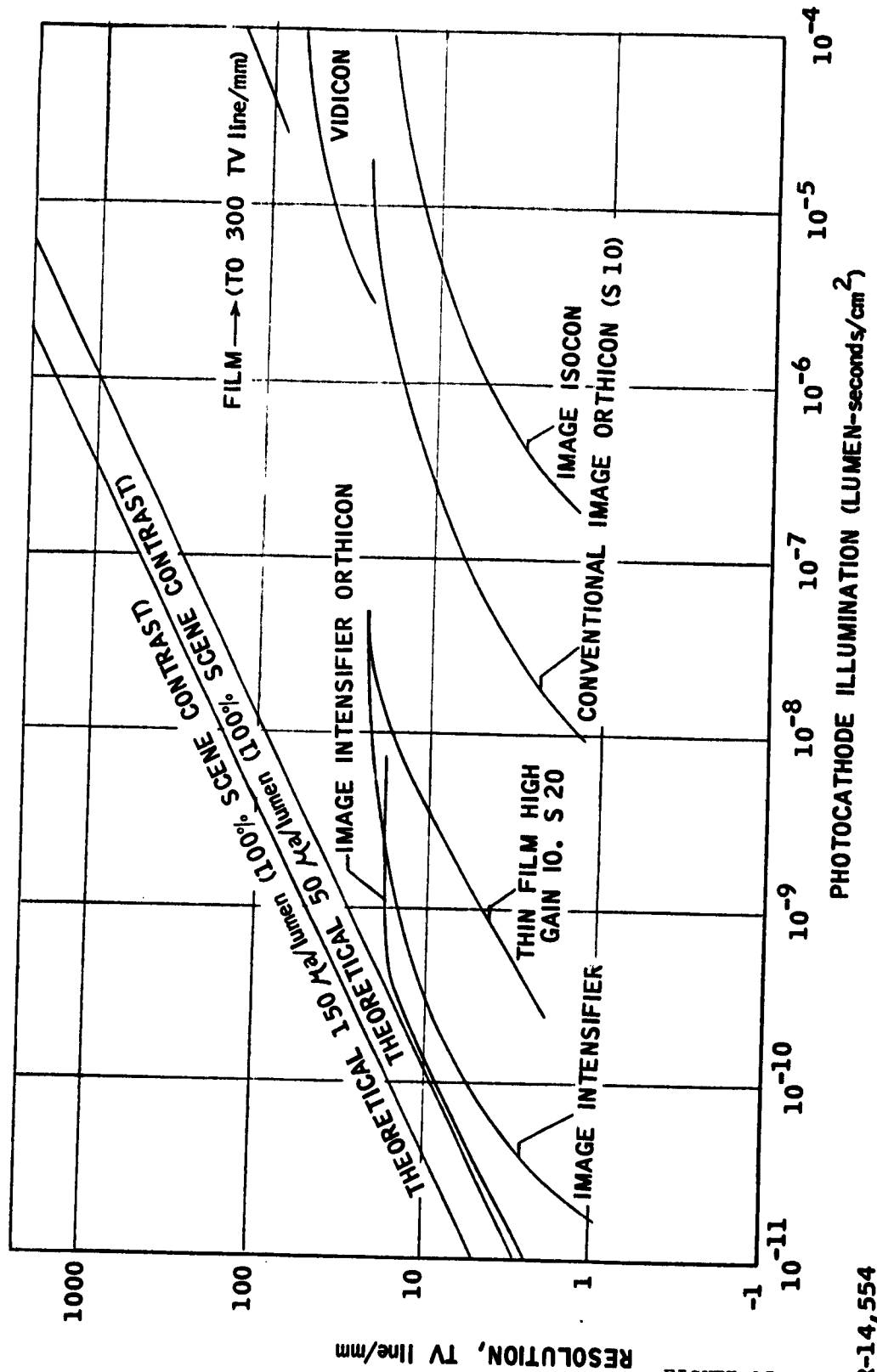
SIGNAL TO NOISE RATIO (S/N) AS A FUNCTION OF PHOTOCATHODE
ILLUMINATION FOR SEVERAL SENSORS

FIGURE 14

R14,552
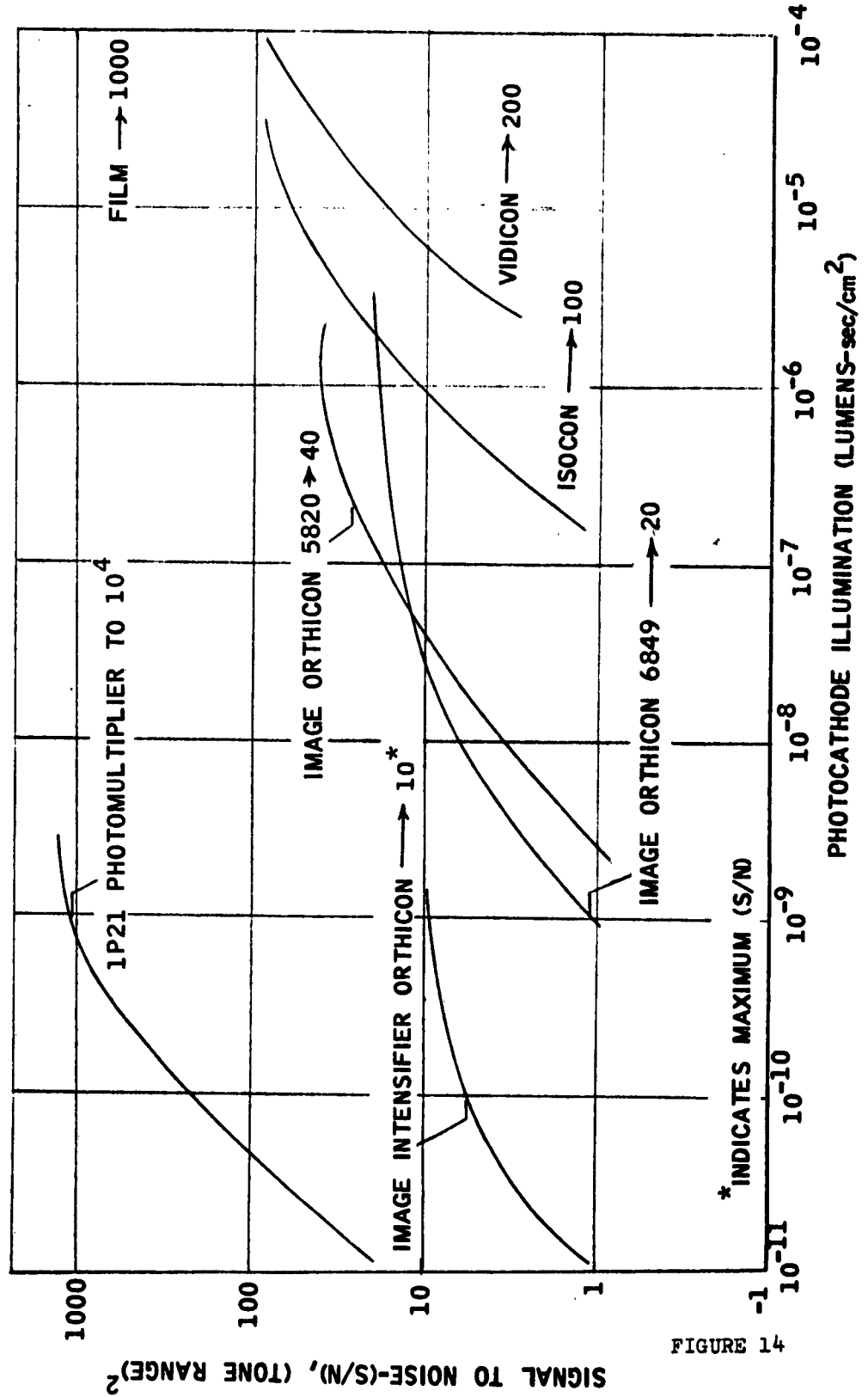
SPECTRAL IRRADIANCE Hs REQUIRED AT ENTRANCE APERTURE
OF 1cm2 FOR DETECTION OF MINIMUM NUMBER OF PHOTONS
(S/N = 1) WITH DIFFERENT INTEGRATION TIMES

FIGURE 15

R-14,553
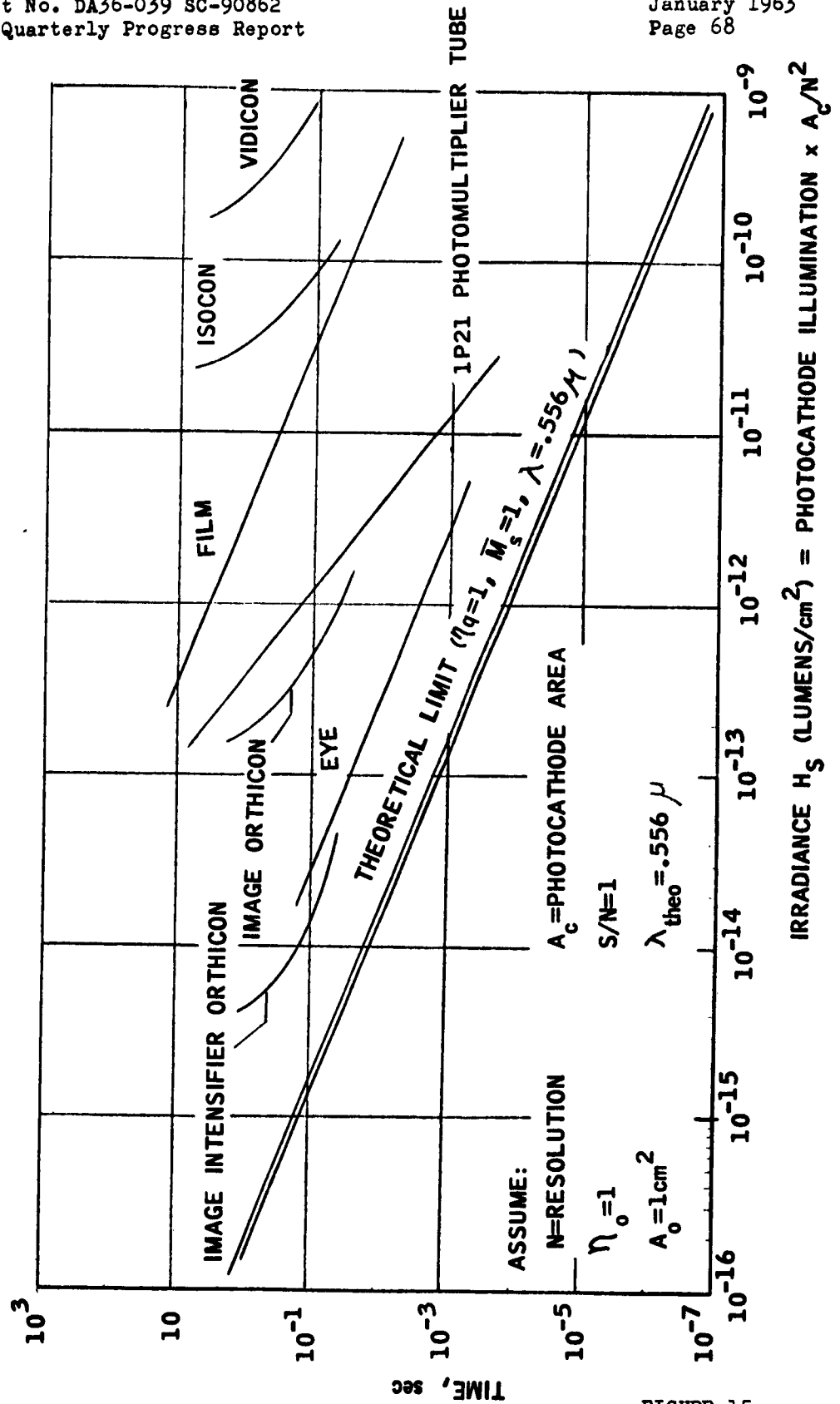
D. RECOMMENDATIONS

The systems analysis work has been concerned with:
(1) completion of the scene composition study; (2) continued analysis
of image transducing parameters; and (3) a preliminary study of read-
out systems. During the next quarter, the following areas should be
accented.

(1) Completion of image transducer parameter studies

(2) Utilization of parameter and scene analysis to
     establish the desired performance parameters of an
     advanced image transducer and translate these into
     appropriate design criteria.

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III.   COMPONENT RESEARCH

A. SUMMARY

Recognizing that the read-out operation is of major
importance in image transducing, a preliminary study of the various
methods of read-out was initiated and completed during this quarter.
Three promising read-out methods are:

(1) Programmed matrix light source with a fiber optic
geometry converter to provide a line scan
(2) Flying spot scanner employing fiber optic conversion
(3) Kaiser Electronics special line scan facsimile tube.

It is shown that the read-out method which will ultimately
be employed in the image transducer is largely dependent on the storage
medium. As the storage medium has not been selected, the foregoing
methods will only be considered in more detail as they become applicable.

Further analytical investigations and the suggested experi-
mental program for electroluminescent matrix light sources requires the
knowledge of the use of the light source in conjunction with other com-
ponents. This investigation therefore has been postponed until the next
quarter.

In the present reporting period two devices were investigat-
ed for possible use as image storage components. The optron consists of
a photoconductor - electroluminophor combination. Half - tone operation
of this device has been achieved for periods as long as one minute. Re-
solutions of 80 lines per inch have been achieved in practice with much

higher resolutions possible in theory. Response time - sensitivity products
of 0.1 foot candle second have been achieved using CdS as the photoconductor.
Considerable improvement on this parameter should be possible by using faster
and more sensitive photoconducting materials.

The ferrotron can also be used for purposes of image
retention. It consists of a photoconductor - ferroelectric combination.
A breadboard version of this device has been operated at readout speeds of
50kc. A resolution of 200 lines per inch with a sensitivity of 0.001
foot-candles has been reported. Further investigation of this device for
possible application in the proposed image transducer should prove fruitful.

In the previous reporting period it was suggested that an
ordered fiber optic array offered a possible method of high resolution image
dissection. In this reporting period the possible fabrication of such a
device was investigated. Several methods capable of automatically fabricat-
ing the desired ordered array were evolved. The extremely large size of the
ordered array required for the present system suggests that the cost of
developing such a device would be prohibitive for the near future.

B. COMPONENT TECHNIQUES -- READ OUT METHODS

1. General

Consideration of the functional breakdown of an image transducer system indicates that the read-out operation is of major importance. This section will be concerned with several read-out systems and their respective components.

The read-out system employed will necessarily depend upon the characteristics of the storage medium. Many storage media will store the input optical image in a form which can be interrogated with a beam of light. However, the optical image could be stored in a form which could be read-out in correspondence with the light input level. This storage medium would require only a sensor and a moving aperture for read-out. This discussion will consider only these storage media which employ a beam of light or an electron beam and a photo sensor for interrogation and read-out of the storage medium.

A scan in both X and Y coordinates is necessary to interrogate the complete area of the storage medium. Scan generation can be accomplished by use of either a raster scan or line scan with coincident movement of either the light source or of the storage medium to provide the other scan dimension. The line scan coupled with movement of the medium requires a more complex mechanical arrangement but offers better positioning accuracy.

The methods of generating a scanning light beam include:

a) A programmed matrix light source

b) A flying spot scanner

c) Special line scan tubes such as those developed by CBS
   and Kaiser Electronics

d) Mechanical scanning.

Read-out syst ms employing the above methods are
discussed in the subsequent sections.

2. Programmed Matrix Light Sources

A matrix light source consists of a large number of
individually energized light elements. As pointed out in the First
Quarterly Progress Report, this light source can achieve very high
positional accuracies; is not limited in its scan length capability;
can produce a reasonable light output; and, it appears, can yield high
scanning speeds. If, however, a 10,000 line resolution is desired and a
single light source is required per image element, 10^8 light sources
would be needed. Two major problems associated with a matrix light
source of such a high packing density are:

1) Fabrication problems

2) Switching configuration

The fabrication of a matrix light source with a pack-
ing density in the order of 10^8 elements in a reasonably small area
would require an extensive research and development program.

High speed commutators provide the most basic method
of successfully switching each element of a matrix light source. In
practice, two commutators would be used, one commutator to switch the

lines of the matrix and the other to switch the columns. The voltage
is applied sequentially to each element of the matrix by allowing the
column commutator to complete a full cycle of operation for each succes-
sive position of the line commutator. With this basic arrangement, a
total of 20,000 switch positions would be necessary to achieve a re-
solution of 10,000 lines and 4,000 switch positions for 2,000 line
resolution.

The commutation or switching process may be accomplish-
ed mechanically or electronically. The mechanical method, utilizing a
rotating switch, suffers disadvantages in operating life and limited
operating speed. Straight-forward electronic switching, employing some
form of counter driving a diode switching matrix, would demand an excess-
ive number of circuit elements to provide 10,000 discrete outputs for
each axis.

A more sophisticated method of switching might be
achieved by the use of a line scan in conjunction with movement of the
storage medium. A square matrix light source of 10,000 elements, pro-
grammed by two 100 position electronic commutators, would provide a
sequentially switched light source. The line scan is obtained by using
fiber optic conversion to change the elements of the square matrix to a
line of 10,000 positions.

The method of switching proposed above overcomes the
two major problems associated with the use of a programmed matrix light
source for read-out. The packing density of the source is reduced by a
factor of 10^4 and the number of switching elements is greatly reduced.
A 10,000 element matrix light source and the proposed fiber optics con-
verter can both be realized by present state-of-the-art techniques. In

view of this, a more thorough analysis of this read-out method should
bw undertaken in order to determine its feasibility.

3. Flying Spot Scanner Read-Out

A flying spot scanner could be used to generate the
scanning light beam for interrogating the storage medium. This scanner
could generate either a raster or a line scan pattern. This system,
however, has several major problems. First, its line scan to spot size
ratio, a measure of its read-out resolution capability, is limited.
Secondly, the intensity and spectral distribution of its light output
is also limited. Beam positioning accuracy, the uniformity of its
light output, and light spot "halo" and "trailing" effects are other
problem areas that must be considered with the flying spot scanning
system.

Some present day flying spot scanners are capable of
schieving .003 inch spots over an approximately 4" scan in a 5" CRT tube.
This would represent a read-out resolution capability of approximately
4/.003 or 1,330 lines, which is far short of the 10,000 lines desired.
These scanners can achieve positioning accuracies of 1% which is con-
siderably poorer than the .01% desired.

The desired resolution and accuracy could, however, be
achieved in a flying-spot scanner system by using fiber-optic geometry
converter and a line scanning read-out system. In this case, the fiber-
optic scan converter would convert a ten-line, 1000 element/line, raster
scan pattern on the flying spot scanner into a single 10,000 element
horizontal scan at the storage medium. As conical fibers would be em-
ployed, the read-out beam positioning accuracy would be considerably
higher than that of the C. R. T. By embedding these fibers into the

face-plate of the flying spot scanner, considerable improvements in
optical efficiency can also be obtained.

4. Special Line Scan Tubes

Special modifications of the flying spot scanner
could be employed to yield higher scan length/spot size ratios. One
such device, the CBS line scan tube, has the phosphor coating on a rotating
drum, inside of a CRT, thus alleviating problems in phosphor burn-out
and fatigue. It also utilizes the light spot generated on the electron
beam side of the phosphor. On conventional CRT's, the light spot on the
outside of the phosphor is employed. This light spot is larger than that
on the inside because of light and electron beam spreading through the
phosphor.

Kaiser Electronics of San Jose has proposed a special
line facsimile read-out tube (see Figure 16) which deflects and focuses
the scanning electron beam in a unique manner. The use of a line scan
read-out allows the use of a compact cylindrical tube with deflection in
only one axis. The spot size may be independent of scan length, an ad-
vantage which is not realized by conventional flying spot scanner systems.

5. Mechanical Scanning

The scanning light spot can be generated mechanically.
In general, mechanical scanning methods are limited in scanning velocity
but realize advantages in spectral range, scan length spot size ratios,
intensity, and lack of after-glow. The generation may be accomplished
by rotating lenses, a rotating mirror, or rotating glass fibers.

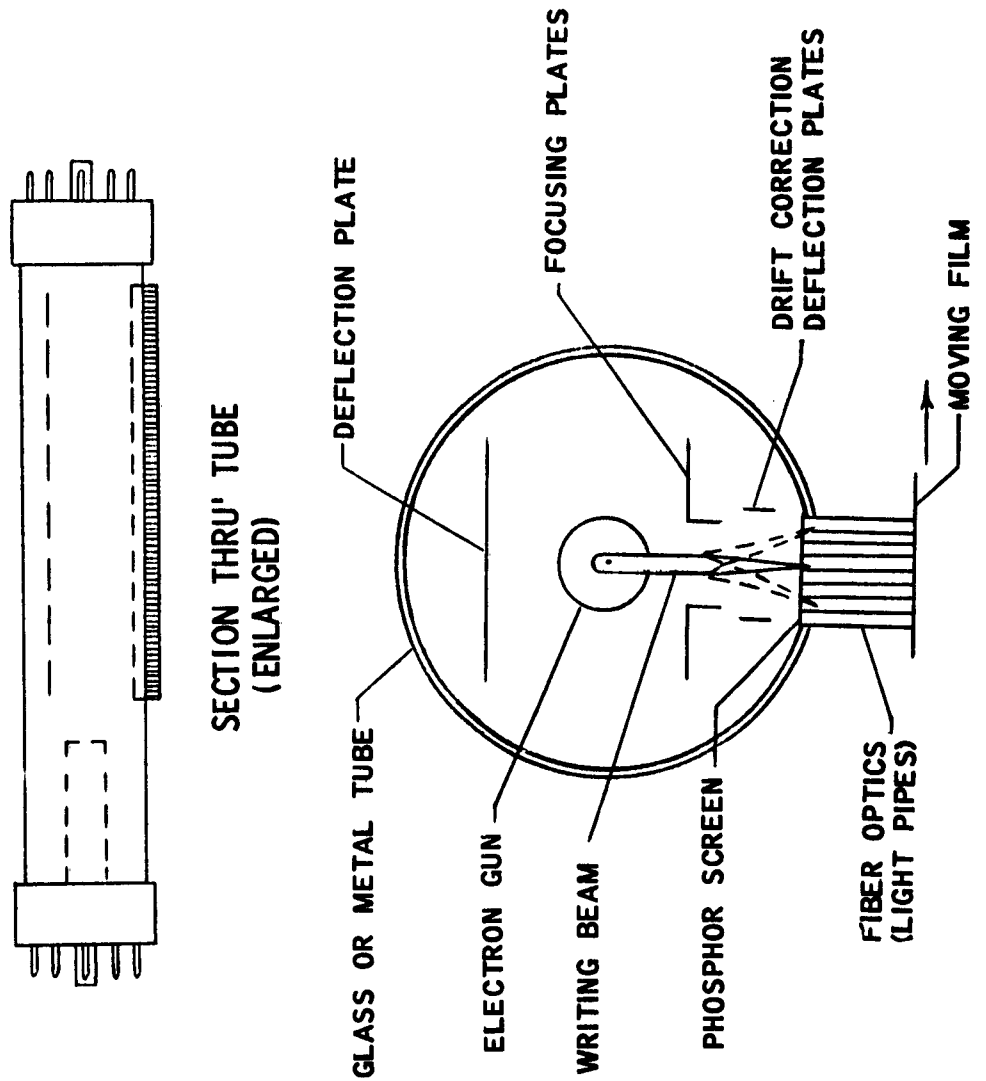FIBER OPTICS WINDOW
KAISER-AIKEN FACSIMILE TUBE

SECTION THRU' TUBE
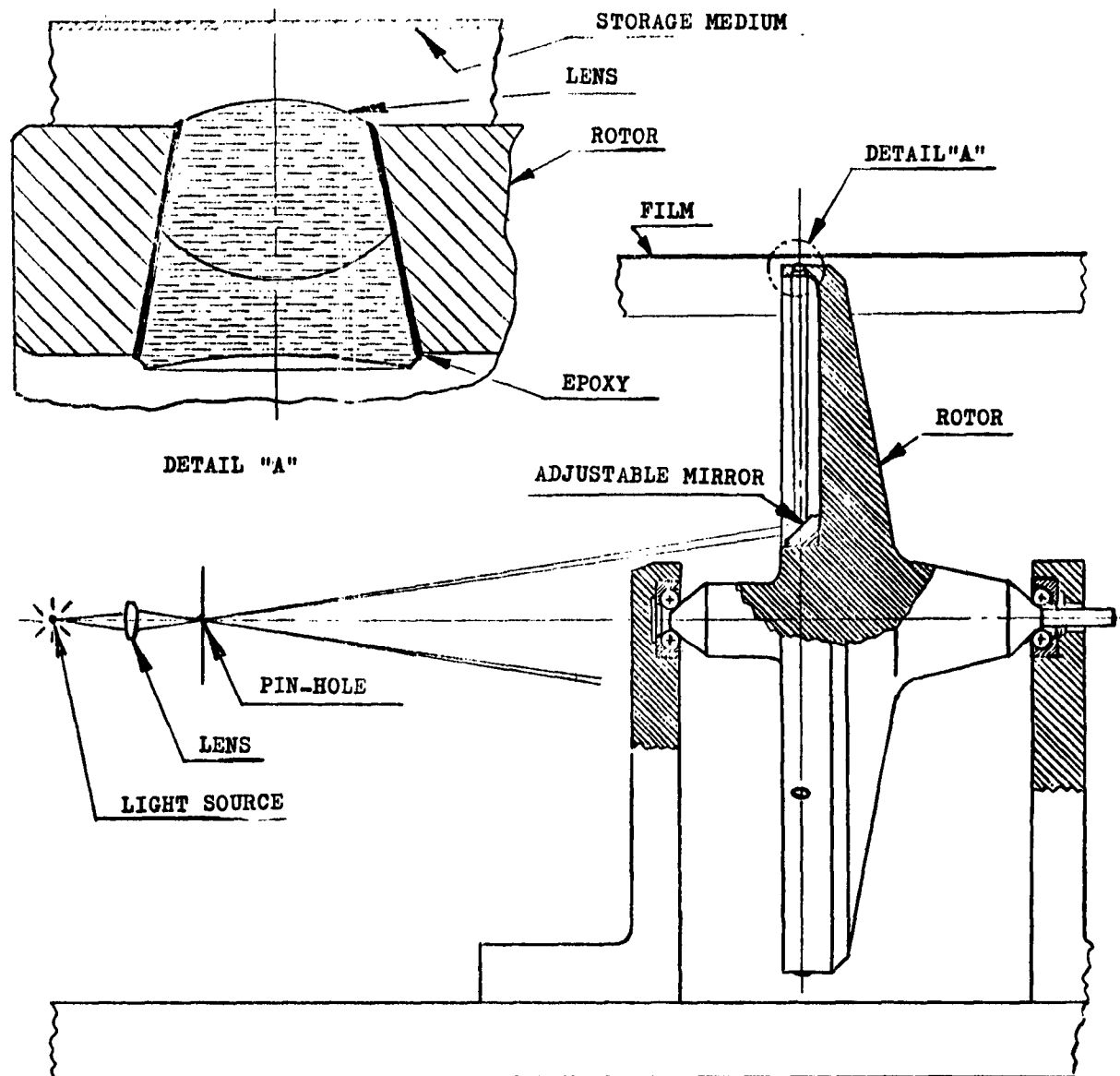(ENLARGED)

FIGURE 16

R-14,561

A moving light spot can be generated mechanically by
means of pinholes in rotating discs, drums, or belts. Each of these methods,
however, requires a unfirom light source of high intensity extending over
a large surface area which is difficult to achieve.

In the moving-lens scanning system, such as shown in
Figure 17 the scanning dot is produced by means of a number of lenses
mounted to a common rotor. Three lenses focus light from the light sources
onto the storage medium and the motion of the rotor produces a line scan.
Information is obtained from the moving storage medium. The transmitted
light is collected and relayed to a photomultiplier.

A typical moving-mirror scanning system is shown in
Figure 18 The pinhole is located at the axis of rotation. Its light
is collected by a rotating elliptical mirror and projected onto the
storage medium. Multi-surface mirrors could be employed for producing
several scan lines per mirror revolution.

The scanning spots can also be generated by means of
moving glass fibers. A typical system is shown in Figure 19 The
fibers, one for each scanning spot, are mounted in a rotor. The entrance
ends are located at the axis of rotation and are illuminated by means of
a small, intense light source and lens. The light output ends move in a
circle very close to the storage medium. That light which passes through
the storage medium is collected and sent to the photomultiplier.

STORAGE MEDIUM

LENS

ROTOR

DETAIL "A"

FILM

EPOXY

ROTOR

DETAIL "A"

ADJUSTABLE MIRROR

PIN-HOLE

LENS

LIGHT SOURCE

NOTE: THE LENS IS SHOWN SCHEMATICALLY ONLY THE RADII ARE NOT CALCULATED

MOVING LENS SCANNING SYSTEM

FIGURE 17

SINGLE-MIRROR SCANNER

LIGHT SOURCE

LENS

PIN-HOLE

SCANNING MIRROR

SYNCHRONOUS MOTOR

n = 48,000 RPM

STORAGE MEDIUM

STORAGE MEDIUM

LENS
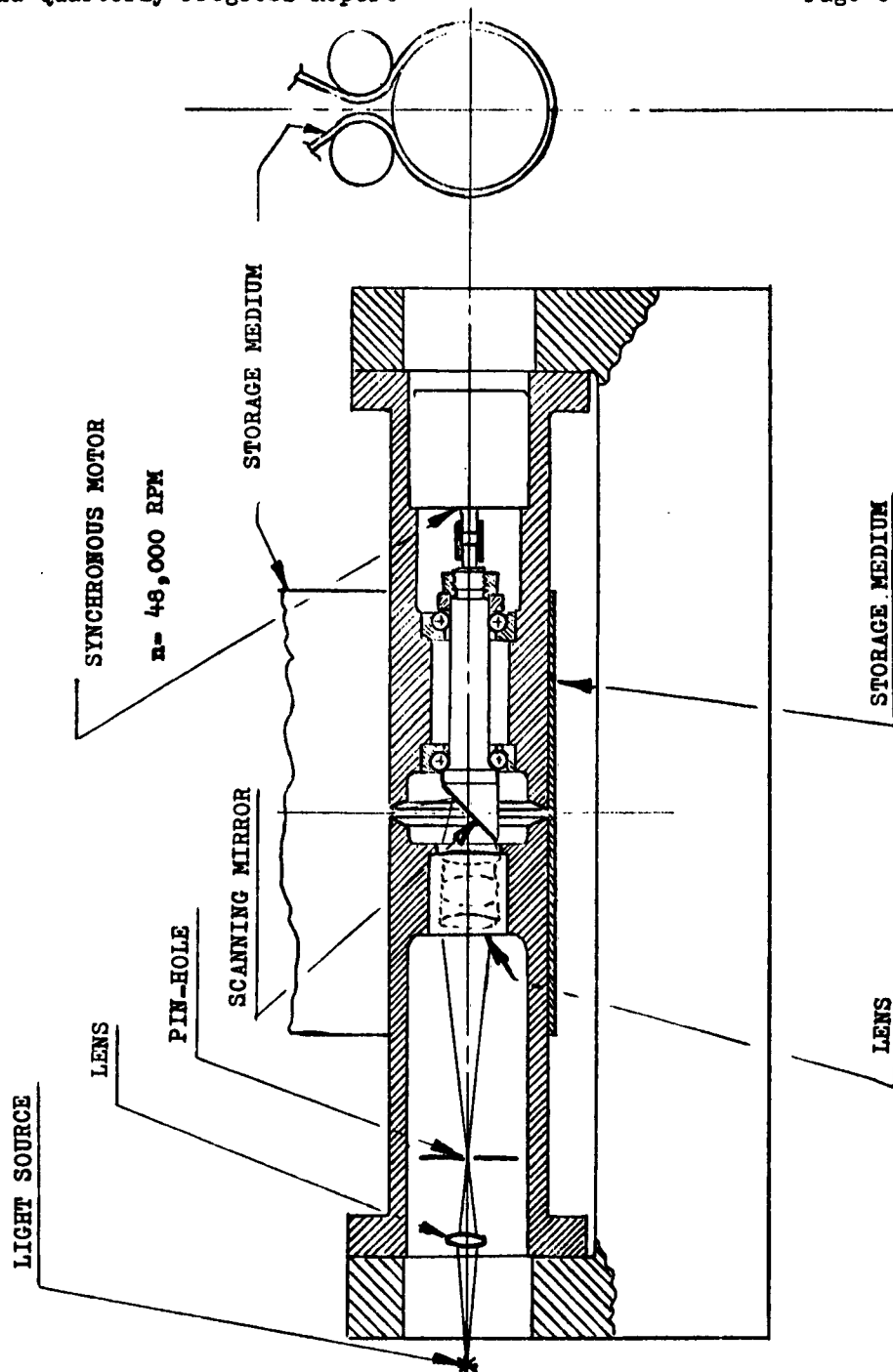
R 14,550

FIGURE 18

CROSS-SECTION THROUGH 360° MIRROR LIGHT-
COLLECTING SYSTEM

SCANNING DOT

STORAGE MEDIUM

ROTOR

LENS

LIGHT SOURCE

BEARING

GLASS FIBER

SPHERICAL MIRROR

SCANNING BUNDLE

AXIS OF
ROTATION

CENTER OF
SPHERICAL MIRROR

APERTURE STOP

PHOTOMULTIPLIER TUBE

FIGURE 19

R-14,551

C. IMAGE RETENTION DEVICES

An important function to accomplish in the proposed
image transducing system is that of image retention. The reason for
this is that the scene exposure time is only 10 milliseconds while
transmission of the image may require considerably longer times.
Thus, to have the scene available for transmission operations longer
than the 10 millisecond exposure time, it is necessary to provide
for temporary image storage.

In the present report period two devices capable of
image retention were investigated. These devices (the optron and
ferrotron) are discussed in this section.

1. Optron Matrix

Materials such as double activated phosphors and
those exhibiting phototropism are capable of retaining a latent
optical image. It is also possible to retain an active optical
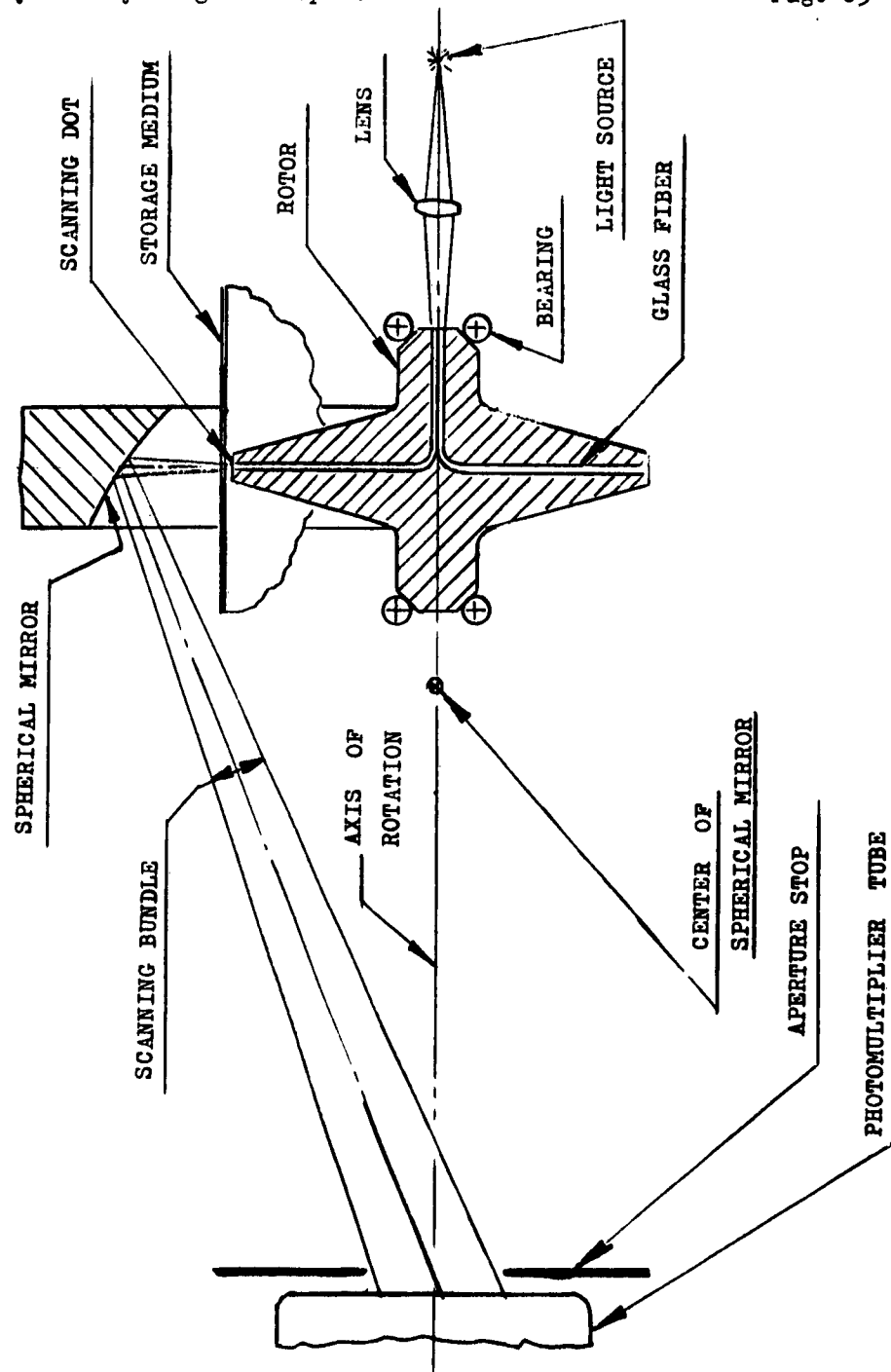image by combination of certain types of materials. One possible
device, consisting of a combination of an electroluminophor and
a photoconductor, called an optron, will be discussed here. A
matrix of optron elements could be employed to store an optical
image. The cell construction of an optron element is shown in
Figure 20. The light emitted from a light source (image) strikes
the photoconductor, thus increasing its conductivity and simul-
taneously increasing the voltage across the electroluminor. The
electroluminor is thus excited and emits light. A part of this light
serves as the output signal (retained image) and part is fed back
to the photoconductor to sustain the excitation when the input
light source is extinquished. Such panels have already been

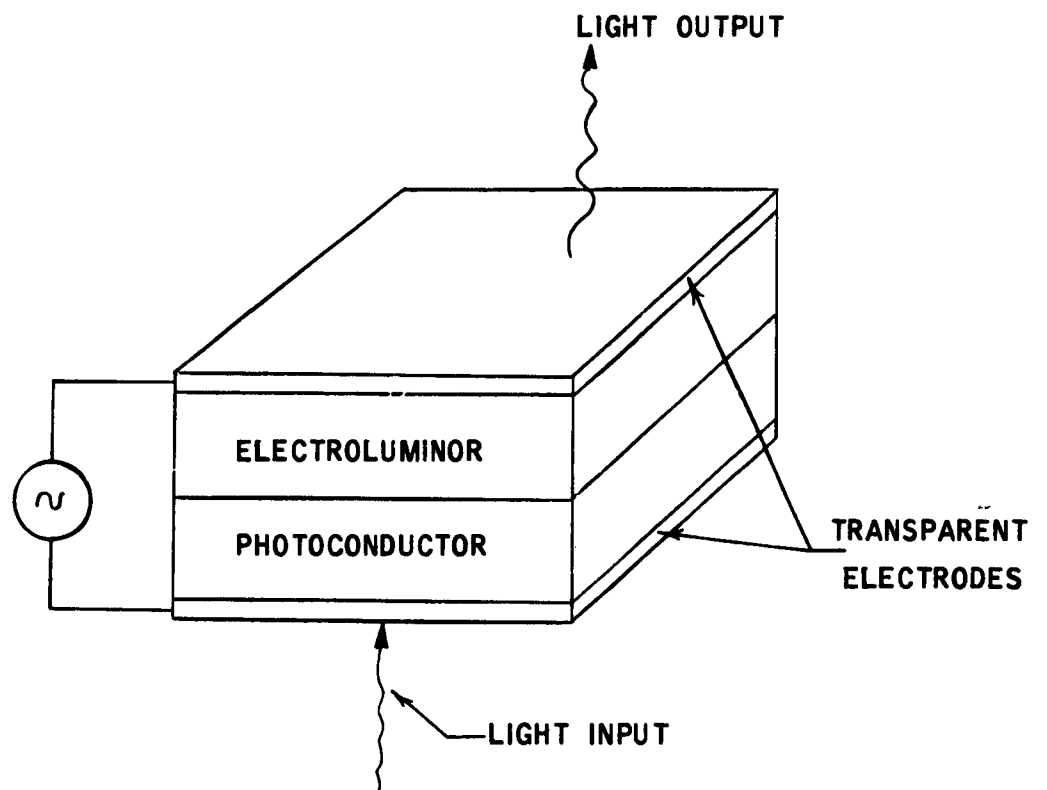## OPTRON STORAGE ELEMENT

FIGURE 20

extensively discussed in the literature and several such devices have
been constructed. The resolution of existing devices is a little below
that desired in this application. However, this appears to be a
matter of improvement on the state-of-the-art as no fundamental
limitations prevent reaching the desired resolution.

With sufficiently high level inputs the optron
unit shown in Figure 20 can be operated in a bistable mode. Operated
in this way the unit is essentially a storage element with two states,
dark (off) and fully lit (on). For present purposes this is undesir-
able since several shades of gray are required. If the unit is
operated below this critical input level, it no longer acts as a
stable memory. However, the closer to the critical level the device is
operated the longer it takes for the image to decay. Half tone
operation[2] for such panels has already been achieved for times
greater than one minute.

A possible modification of the optron storage
element is shown in Figure 21 . Here several layers of different
photoconducting materials are used rather than one. The photo-
conductors are chosen such that different light levels are required
to trigger them. In this way one layer after another is rendered
conducting by increasing the input light level, resulting in
multimode storage operation. In theory any number of layers
could be used and hence any number or modes obtained. In practice,
of course, the number of layers will be limited by thickness
considerations as absorption of the light energy increases
rapidly with increasing thickness. Preliminary experiments would
be essential to determine the limitation on the number of usable
layers. The memory time of such a device is essentially infinite
since it operates in a multi-stable mode.
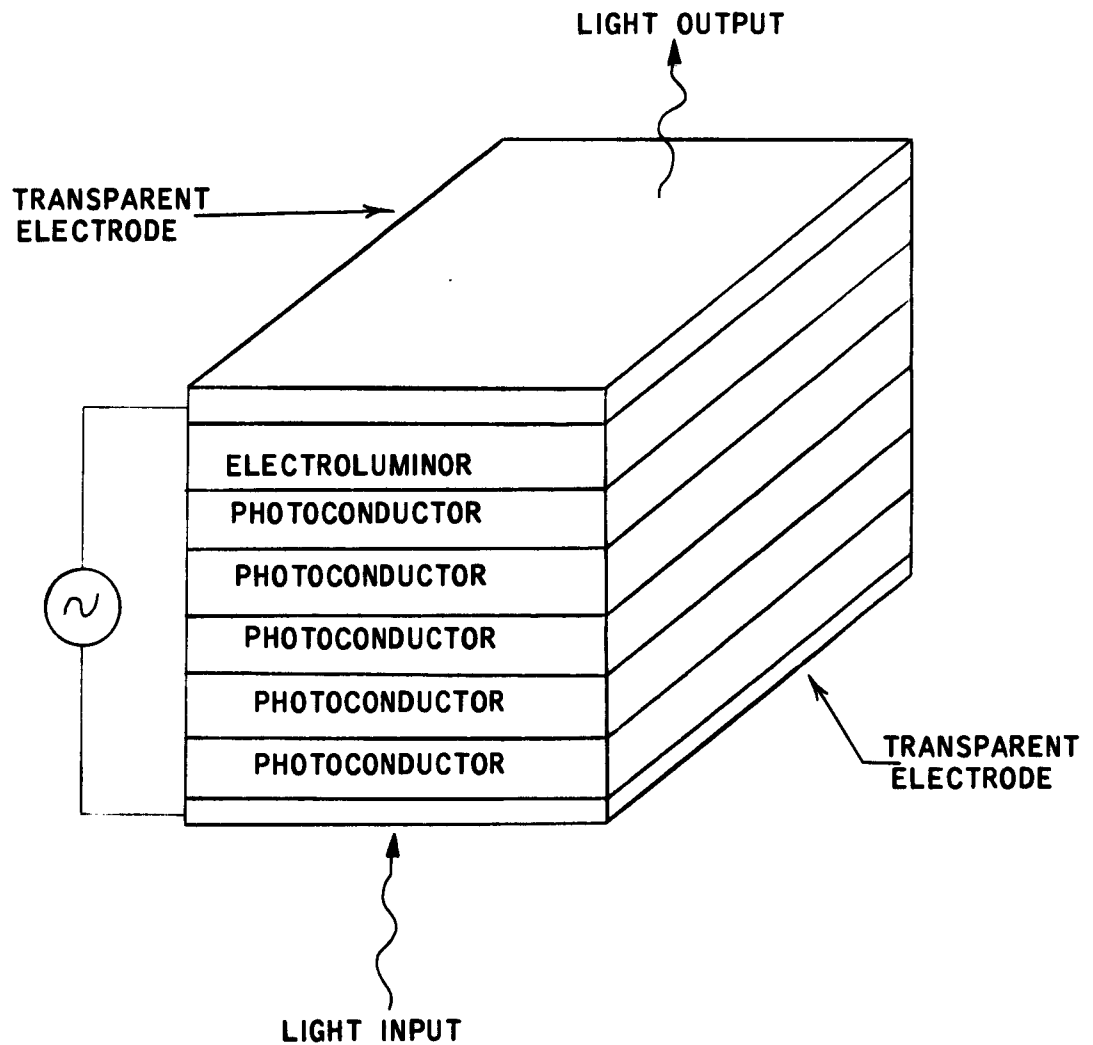
MULTIMODE OPTRON STORAGE ELEMENT

LIGHT OUTPUT

TRANSPARENT
ELECTRODE

ELECTROLUMINOR

PHOTOCONDUCTOR

PHOTOCONDUCTOR

PHOTOCONDUCTOR

PHOTOCONDUCTOR

PHOTOCONDUCTOR

TRANSPARENT
ELECTRODE

LIGHT INPUT

FIGURE 21

An optron matrix is shown schematically in Figure 22
The individual cells are optically insulated to prevent crosstalk.
Existing optrons trigger at input light levels of the order of 0.1
foot candle second. This sensitivity can be improved greatly by
employing photoconductors other than those presently used. Existing
devices tend to contain materials which are both insensitive and have
long response times. Proper choice of the photoconducting material
should improve this situation considerably.

2. Ferrotron

Photoconductors, which detect light, and ferro-
electric materials, which store information, have been wed together
to store light images. This section describes the operation of
this light storage device in an image storage and retrieval system.
This device will be referred to as a ferrotron.

The light storage element consists of the necessary
electrodes and layers of photoconductive and ferro-electric material
(Fig. 23). In operation the incident light decreases the resistance
of the photoconductor while simultaneously the programmer momentarily
closes switch X permitting a voltage to be applied which polarizes
the ferroelectric. The degree of polarization of the ferroelectric
cell is determined by the applied voltage, the length of time the
switch is closed and the resistance of the photoconductor (which is
a function of the incident light level). The ferroelectric
material can store amplitude levels, providing the storage element
with a tone range capability.

It is thus seen that the switch "on" time "t" can
be varied to establish the sensitivity of the storage device. Where
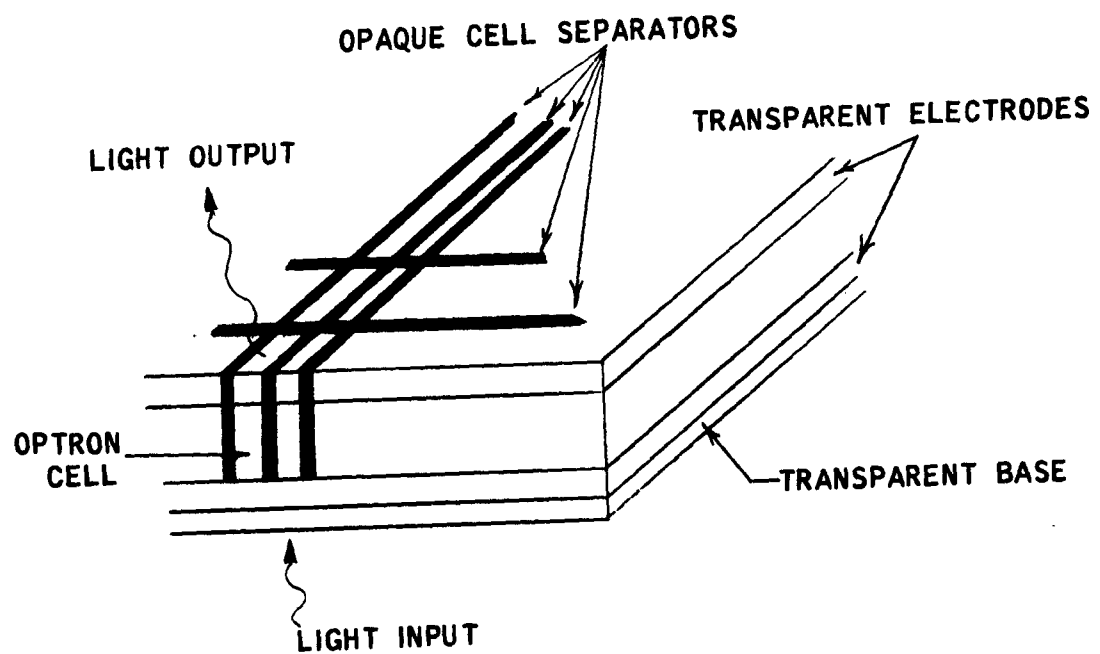the average light level is high, the pulse duration will be short.

OPTRON MATRIX

OPAQUE CELL SEPARATORS

TRANSPARENT ELECTRODES

LIGHT OUTPUT

OPTRON
CELL

TRANSPARENT BASE

LIGHT INPUT

FIGURE 22
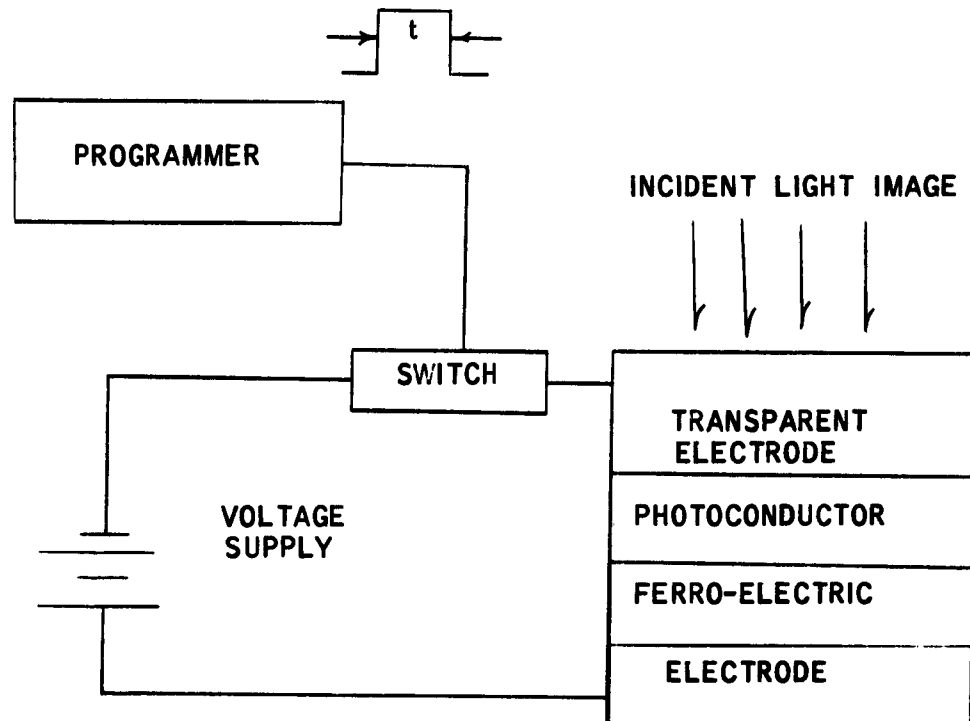
LIGHT STORAGE ELEMENT

FIGURE 23

When operating at night (low light levels), the duration time can be
increased to provide higher image storage sensitivity.

Multi-element image storage screens can be
prepared by depositing layers of photoconductive (such as cadmium
sulfide) and electrode material (gold) on a ferroelectric slab
similar to the arrangement shown in Fig. 24 . In operation, the
image side of the screen is exposed to the incident image light
which changes the resistivity pattern of the photoconductor in
accordance with the incident light level at each point. Switch
"1" is then momentarily closed for a time "t" (determined by the
average ambient light level) polarizing the ferroelectric in
correspondence with the resistivity (and thus light) pattern on
the read-in photoconductor layer.

Readout of the stored image can be accomplished
either optically or electrically. For optical readout a voltage
is continuously applied across the ferroelectric layer and a pin-
point beam of light scans the stored image line by line. The
incident light lowers the resistance of the photoconductive layer
sufficiently to result in a voltage pulse being applied to the
ferroelectric material. This voltage pulse depolarizes the ferro-
electric material, the resultant current being sensed for readout.
This readout method, however, depending upon the speed of the photo-
conduction is relatively slow. Readout could also be accomplished
electrically by laying a grid of conductors on either side of the
ferroelectric layer in the form of a matrix. Each matrix position
could then be sampled sequentially by application of a voltage
pulse.

MULTI-ELEMENT IMAGE STORAGE SCREEN

INCIDENT IMAGE LIGHT

SWITCH 1

VOLTAGE SUPPLY

ELECTRODE GRID

TRANSPARENT ELECTRODE

READ IN PHOTOCONDUCTOR

FERRO- ELECTRIC

READ OUT PHOTOCONDUCTOR

TRANSPARENT ELECTRODE

READ OUT LIGHT SOURCE

VOLTAGE SUPPLY

LEADS TO ELECTRODE GRID

COMMUTATOR SWITCH

INTERRO- GATOR

E_S

FIGURE 24

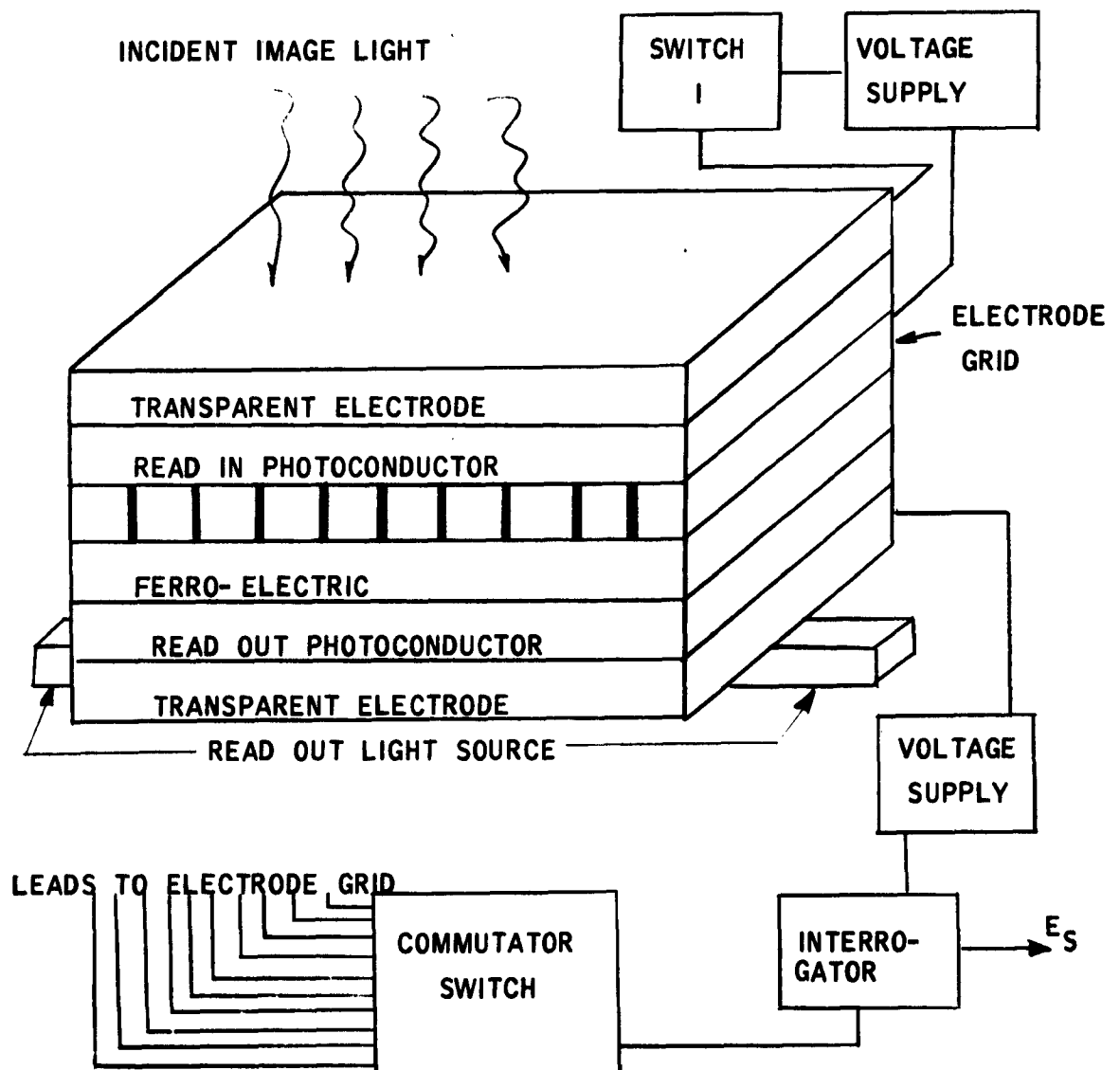In Fig. 24 is shown a complete image retention and
readout technique employing a line of light together with electrical
line commutation   to accomplish readout. The interrogation and
depolarization of all points of the ferroelectric storage layer
is accomplished by moving the light line in incremental steps
and sampling all the conductors of the electrode grid at each of
the light line positions.

D. FIBER OPTIC ARRAYS

      The analysis appearing in the first image transducer
quarterly report indicated that a fiber optic array of five micron
fibers would theoretically dissect a 5" x 5" image with a resolution
of 10,000 lines and a method was shown for separating the image
elements for achieving this high resolution with conventional readout
techniques. However, this would necessitate the construction of an
ordered array of 645×10^6 five micron coated fibers (or 25.9×10^6
fibers for a 2,000 line resolution system), posing a formidable
fabrication problem. A method for simplifying the fabrication
process was presented. This method would consist of automatically
arranging 100 fibers in small coded sections, the final array being
made by mosaicking these sections together. The fibers in each
section would be interwoven to separate the image elements in the
output plane for high resolution readout. This section discusses
the present state-of-the-art of producing coated fibers and unordered
fiber bundles and suggests several methods which might be employed
to automatically fabricate ordered fiber arrays.

      Methods of drawing lengths of high refractive index
glass fibers with a thin coating of low refractive index glass and
methods for drawing multiple unordered fibers have been developed[1].
The insulated fiber drawing machine is illustrated in Figure 25. The
rod and its tubing are fed, at constant speed, into a hollow
cylindrical furnace. Here they are heated sufficiently to cause
fusion of the two materials and tapering of the fiber down to very

(1) Page 210-213 "Electro-Optical Systems Using Fiber-Optics", by
    N. S. Kapany, Optica Acta, Vol. 7, No. 3, July 1960.
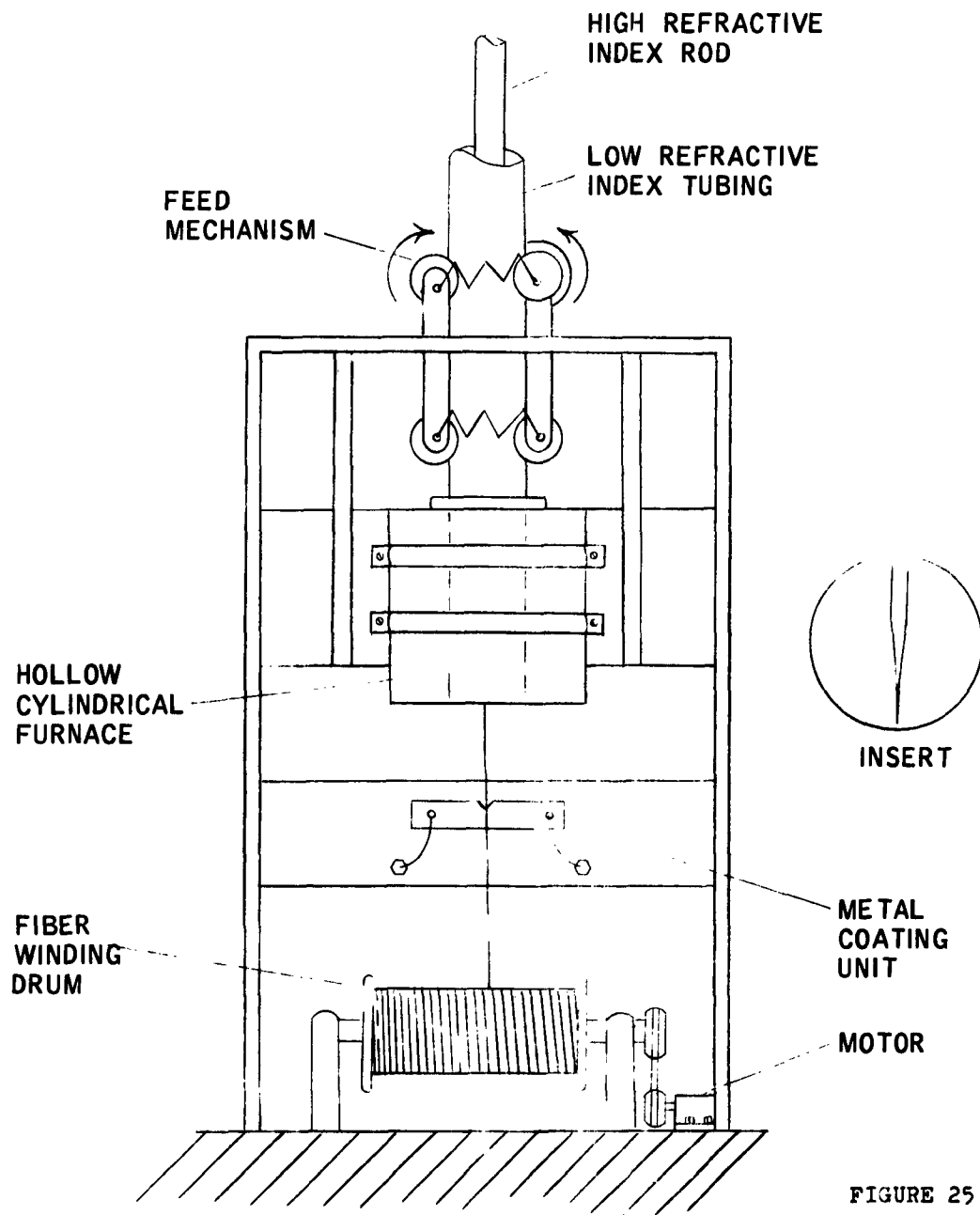
INSULATED FIBER DRAWING MACHINE

FIGURE 25

small diameters (see insert). The resultant fiber diameter is determined
by the size of the original rod and tube, the rate of feed, the
furnace temperature and the speed of the winding drum. A second
metal insulating coating can simultaneously be deposited on the
fiber by the metal coating unit shown in Figure 25. This is
accomplished by passing the fiber through molten metal such as
aluminum or indium, which deposits a continuous and uniform metal
coating around the fiber.

A method of producing a new type of fiber consisting
of a large number of very small diameter fibers has been developed.
These "multiple fibers" are made in the same manner as the single
coated fiber described above. However, in this case a large number
of coated rods are bundled together and passed through the drawing
machine. Multiple fibers consisting of as many as 275 fibers having
2 micron diameters have been drawn by this method but these fibers
were not ordered.

Two methods of automatically arranging a fiber bundle
are described below. In the system shown in Figure 26a the fiber
ends would be sequentially directed to their desired locations by
air flow. Individual fibers would be fed into the air chamber.
A programmed valve would uncover the appropriate hole in the
acceptor plate, permitting air to flow only through it. The air
flow would direct the fiber to the uncovered hole where it would be
captured and held. The next fiber would then be fed into the chamber
and similarly directed to its desired end position on the acceptor
plate. The process would be repeated until the entire fiber section
is formed. The fiber ends would then be cut and stacked and
cemented together to form the ordered section. The sections, in turn,
would be stacked together to form the final fiber array.

Another method would utilize holes which can be positioned in the acceptor plate to arrange the fibers in the desired pattern. In the initial step of the operation, the acceptor plate would be adjacent to the feeder plate (Figure 26b), the holes in the two plates being in alignment at this time.

The fibers would then be fed into the holes of the acceptor plate, at which time the holes in this plate would contract, locking the fibers. It then would move away from the feeder plate into the position shown in Figure 26c. These holes would then be repositioned into the desired arrangement (Fig. 26d), both ends cut and the fibers bundled and cemented together to form the 100 fiber ordered section. Such machines are highly complex, and, because of the fragility of the fibers, would require a large amount of experimental research and development. Furthermore, assuming the cost of ten fibers to be one cent, the cost of the fibers alone ($645,000 for 10,000 line resolution) makes them impractical for this application.

The inter-leaving of 100 five micron fibers to form one ordered fiber section is a formidable task. As 6.5×10^6 of these sections would be required in a complete 10,000 line resolution fiber optic system, the fabrication cannot be done manually. The small fibers are extremely fragile, making any mechanical manipulations very difficult. Machines and techniques have been developed for drawing fine insulated fibers and un-ordered multiple fibers, consisting of as many as 275, 2μ diameter fibers. However, these techniques are not directly applicable to the solution of the present problem. It appears that the solution would require a large advancement in the state-of-the-art of fiber handling and weaving. This, together with the high cost of producing the required fiber array renders this approach impractical at this time.

METHODS OF FIBER FABRICATION
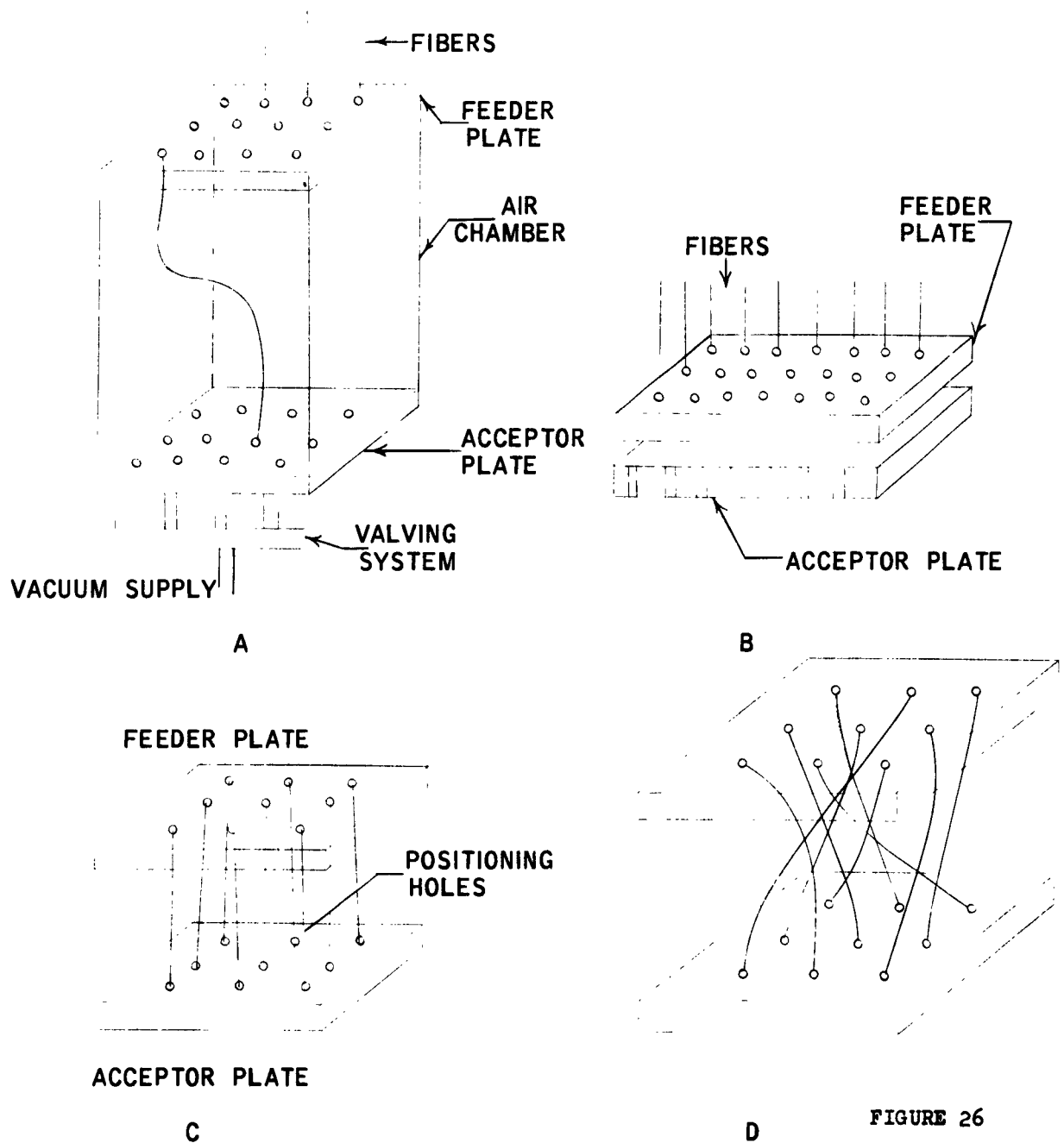
FIGURE 26

E. RECOMMENDATIONS

During the next report period investigations should be
carried out in the following areas.

(1) The compatibility of various components used in combination
to form an image transducing system should be studied to
determine an optimum performance system.

(2) The investigation and study of solid state light storage
elements should be placed on determining the operating
parameters such as sensitivity, resolution, noise
characteristics, dynamic range, response times and other
pertinent parameters.

(3) Analytical and experimental investigations should be
carried out leading up to the design and construction of a
breadboard matrix electroluminescent light source. The
performance parameters should be ascertained to determine
the feasibility of this type device as a matrix light
source.

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IV   MATERIAL STUDY

A. SUMMARY

During the past quarter an extensive survey of the
literature was carried out to determine the capabilities of materials
exhibiting phenomena which could be useful in an image transducing
device. These phenomena had been identified as electroluminescence,
double activated phosphorescence, photoconductivity and phototropism
in the previous Quarterly Report. This aspect of the literature
survey is essentially complete. The data obtained will be analyzed
and a selection of a material (or materials) for the contemplated
image transducer made. The complete survey will also include a
full understanding of the image retention capabilities of ferro-
electric materials.

The electroluminescent materials have band widths
typically of the order of one to two thousand Angstroms centered
in any part of the entire visible spectrum, the near ultra-violet,
or the near infrared. Injection electroluminescence has the
advantage of low excitation voltages, ranging from 10 to hundreds
of volts, and short decay times, of the order of microseconds or
less. These properties make the electroluminescent materials useful
as a cold light source of small size capable of being turned on and
off rapidly.

The information available on double-activated phosphors
is somewhat limited, although information on infrared stimulable
phosphors is more abundant. Standard VI and VII appear to be the
best available infrared stimulable phosphors at this time. Standard
VI is excited in the blue-green and emits in the orange-red whereas
Standard VII is excited in the near ultra-violet and emits in the
green. The double activated phosphors are of special importance

for image retention devices.

Photoconductors can be obtained with a great range
of thresholds. Normally the response is found to peak at a wave
length corresponding to the energy gap of the photoconductor.
Consequently, photoconductors can be obtained with peak responses
ranging from the near ultra-violet to the far infrared. The more
sensitive photoconductors tend to have the longer response times
although lead selenide and lead telluride appear to be exceptions.
A sensitivity of 10^{-11} to 10^{-12} watts with a response time of ten
microseconds is possible in the infrared. Photoconductors are
of fundamental importance in devices which convert an optical
image into an electrical image.

The phototropic materials by and large do not appear
to hold as much promise for image storage as do the electrolumin-
ophors, photoconductors, and double activated phosphors. The
best available phototropic material is pink hackmanite although
the sensitivity is rather low. In addition the problem of fabri-
cation in a suitable form exists.

Experiments were made to develop a transparent
synthetic form of hackmanite through a novel approach employing
elevated temperatures and pressures in the forming process.
Fourteen attempts at producing suitable wafers were made. While
complete success was not achieved, steady improvement in the
results was noted. Further experiments along these lines will
be made.

B. LITERATURE SURVEY

In the previous quarterly report it was pointed out that an image transducer requires materials having suitable properties to convert photon into electron   energy or electron into photon energy and for the retention of the image whether in optical or electrical form.

Materials can accomplish the above objectives through either physical or chemical processes. The most promising phenomena associated with these reactions for image transducing have been determined as follows:

Phenomena	Photon to Electron	Electron to Photon	Image Retention	
			Optical	Electrical
Physical:				
Electroluminescence*		x		
Photoconductivity*	x			
(and associated				
phenomena)				
Double Activated			x	
phosphorescence				
Phototropism			x	
Ferroelectricity				x
Chemical:				
Phototropism			x	

* These phenomena often occur together.

The research for literature and the examination of materials has been conducted in consideration of the foregoing table.

1. Electroluminescence

Light may be generated by the direct action of an
electric field (AC or DC) on various solid materials by a number of
different mechanisms. These phenomena are called electroluminescence
and materials which exhibit these phenomena are called electro-
luminophors or electroluminors. Electroluminescence may be sub-
divided into (1) intrinsic electroluminescence (Destriau effect),
(2) injection electroluminescence (Lossev effect), and (3) photo-
electroluminescence. Intrinsic electroluminescence covers chiefly
light emission of suitable phosphor powders embedded in an insulator
and subjected only to the action of an alternating electric field.
Injection electroluminescence covers light emitted by the sole
action of an electric field on crystals or particles in contact
with conducting electrodes so that current injection can occur.
Photoelectroluminescence covers electroluminescent phenomena which
are enhanced through the action of incident radiation. Related to
these three classes of phenomena is a fourth referred to generally
as (4) electrophotoluminescence. Electrophotoluminescence covers
photoluminescent phenomena (i.e., light stimulation by photons)
which are enhanced (or quenched) through the action of an applied
electric field. The characteristics of this phenomenon render it
less difficult than those mentioned above for application in an
image transducer.

The literature on various aspects of these
phenomena is vast with over 500 references occurring since 1955.
H. K. Henisch in a book entitled Electroluminescence, published by
Pergamon Press in 1962, lists 810 references dating back to 1891.
It should be noted that many of the papers appearing in 1961 and
most of those appearing in 1962 are not included in Henisch's

compilation. The field is extremely active at the present time,
both from the research and application points of view. Confronted
with such a huge amount of literature, no attempt has been made to
complete an exhaustive study, but rather it was decided to make a
selective study in order to determine the present state of knowledge
of the phenomena and the materials concerned.

Electroluminescence is normally observed only
in solids. However, certain liquids behave electrically as ortho-
dox semiconductors, raising the suspicion that they may conceivably
be electroluminescent as well. In fact, instances have been
recorded in which contaminated oils have emitted light under high
voltage DC excitation, although it is not clear whether or not
the process can be classified as electroluminescence. Solids which
exhibit electroluminescence may be polycrystalline or single crystals,
but it is not definitely known whether the phenomenon occurs in
non-crystalline solids. Although electroluminors are termed "cold"
light sources, they do in fact heat up somewhat during normal
operation as the energy conversion (electric to light) cannot be
one hundred percent efficient. However, no part of the emitting
surface even approaches the temperature range of incandescence.

Electroluminescence requires the application of
intense electric fields. One method used to accomplish this is to
apply a moderately high voltage across a thin layer of the electro-
luminor. A second method is to make use of the intense electric
fields which exist at pn junctions. Since the light is normally
generated within the specimen, it is essential that it be trans-
parent or at least semi-transparent. Furthermore, at least one of
the electrodes must be semi-transparent to permit the radiation to
be observed.

Within the present context, no distinction is made
between radiation visible or non-visible to the eye. In fact, many
materials emit light in the infrared region of the spectrum. For
some applications, it is quite possible that this would be a
desirable feature. In addition, no single physical process is
implied by the term electroluminescence. On the contrary, many
different mechanisms lead to phenomena legitimately classified as
electroluminescence. Consequently, the survey is divided according
to specimen type. Typical electroluminor parameters discussed in
the following section are listed in Table V for reference.

a. Single Crystals Phosphors

The electroluminescent properties of zinc
sulphide and cadmium sulphide single crystals have been studied
extensively. As systematic studies cannot easily be carried out
using naturally occurring crystals, most studies have been conducted
using laboratory grown crystals. This in itself is a very important
problem which still attracts considerable attention. Present tech-
niques are capable of producing single crystals as large as
40 g. The crystals take the form of rods, plates, or polygonal
prisms with maximum cross-sectional areas of about 1 cm^2. System-
atic procedures have been developed for obtaining crystals of high
purity or for adding various amounts of impurities such as copper,
silver, arsenic, aluminum, gallium or indium.

An important problem which is not yet satis-
factorily understood is that of making low resistance ohmic
contacts to the crystals. Many materials such as aluminum, gold,
silver, beryllium-copper, bismuth, copper, indium, platinum,
tantalum and gallium have been investigated, with best results
generally being obtained with the use of indium and gallium.

TABLE V

SUMMARY OF PROPERTIES OF TYPICAL ELECTROLUMINORS

HOST	TYPICAL IMPURITY	TYPE	OPERATING TEMP.	TYPICAL PEAK EMISSION WAVE LENGTH	COMMENTS
CdS	Cu,Ag, As,	Injectimor intrinsic	Room temp.	5800 A°	Emission seems to be from spots of 10 diam.
ZnS	Al,Ga, In	Injection	" "	5500 A°	Spot emission
Ge	Bo, As	"	" "	17700 A°	Low temp. emission curve depend upon impurity present; pn junction operated in reverse bias
Si	In, Ga	"			
Ge		"			
Si		"		6200 A°	10 μ spot light source
GaP	C, Si, Ge, Mn,S, Zn, Cu	Injection of intrinsic	RT	5900 A°	Reverse currents give increased light
GaSb		Injection	RT	19700 A°	
GaAs		Injection	RT&77°K	10300 A°	
A N	Cu, Mn	Injection	RT	5500 A°	

Of fundamental importance is the location of
light emission. Unfortunately, many investigators merely report
that light originated from the crystals, without any more detailed
identification or description of the emission sources. Some
investigators believe the emission to occur in the immediate
vicinity of the contacts while still others believe the emission
is more or less uniformly distributed over the bulk of the
material. Experimental resolution of this problem is complicated
by the high refractive index of the material. Furthermore, it is
quite possible that both types of emission do occur under different
circumstances. The emitting regions have been studied in some
detail and it appears that emission can occur at discrete spots
rather than continuously. These spots are reproducible and of
extremely small size, probably less than 1 micron in diameter.
The density of spots is not a function of applied voltage, and
interspot distances of 2 or 3 microns have been reported. Other
investigators have reported continuous emission, but clearly a
problem in optical resolution is involved and further experiments
are required to clarify the situation.

A significant anisotrophy in emission
intensity with respect to the relative orientation of field
direction and crystalline c-axis has been reported. The greatest
intensities appear when the applied field is perpendicular to the
c-axis. Experiments indicate that the light emission ratio for
excitation parallel and normal to the c-axis can be as great as
one thousand.

Electroluminescent excitation of ZnS
single crystals can be achieved by constant fields. Under such

excitation, the brightness is found to increase exponentially with
the applied voltage in a reversible manner until electrical break-
down occurs. Moreover, the brightness appears to be directly
proportional to the current density. The brightness-voltage
curves do show some dependence on the type of electrodes used
and emission appears to originate in the vicinity of the electrodes.
Some experiments seem to yield results contrary to those mentioned
above, but it is not clear whether specimens and experimental
conditions were exactly identical. Emission under constant field
excitation cuts off sharply at 3.6 ev (about 3400 Å), peaks broadly
at about 5500Å, and falls off rapidly about 6000Å in some specimens.
Other specimens fail to exhibit emission in the ultra-violet region
of the spectrum.

Single crystals of ZnS electroluminesce
under the action of an applied sinusoidal voltage. The brightness
observed under such excitation is periodic with twice the excitation
frequency. Furthermore, several cycles of operation are required
before dynamic equilibrium is achieved. There appears to be some
disagreement in the literature regarding the location of emission
and its dependence on electrode material. The brightness is found
to increase with applied voltage and excitation frequency. Exci-
tation frequencies as high as 1000 Mc have been used with results
suggesting that inherent relaxation times are probably of the order
of 1 μsec.

Cadmium sulphide single crystals become
electroluminescent in the immediate pre-breakdown region under
DC excitation. At current densities above about 1 amp/cm^2, the
emitted light is readily observed by the unaided eye. As con-
siderable thermal energies are developed at these current densities,

a means of crystal cooling is desirable. The emission generally
occurs in the red-orange, or green part of the visible spectrum.
Emission can also occur in the form of spots with spot size
being of the order of 10 microns. The density and brightness of
these spots tends to increase as the current is increased. Some
cases of electroluminescence at lower applied voltages (two or
three orders of magnitude lower) have also been reported.

Barium and strontium titanates, cuprous
oxide, and titanium dioxide single crystals have also exhibited
electroluminescence upon AC excitation. The emission for barium
titanate is yellow; for strontium titanate, white; for titanium
dioxide, orange white; and for cuprous oxide, infrared. Excitation
frequencies up to 40 Mc have been used in the case of the titanates.
The cuprous oxide also emits under excitation by DC voltages.

b. Electroluminescence at Junctions and
Crystalline Boundaries

The injection of minority carriers at contacts
and junctions frequently leads to electroluminescence. Observations
of this type have been made on germanium and silicon single crystals
with various impurities such as boron, arsenic, indium, and gallium
added. At room temperature, silicon single crystals emit photons
ranging from less than 1 ev. to greater than 1.25 ev. with the
distribution peaking sharply at approximately 1.1 ev. At low
temperatures (77°K), the distribution curves exhibit structure
which is found to be dependent on the type of impurity present.
The addition of indium, for example, shifts the peak of the distri-
bution to about 0.96 ev. In all cases the emission is confined
to the infrared region of the spectrum. This is to be expected
as silicon has a forbidden region of only 1.1 ev. at room temper-
ature. Similar results were obtained for germanium with a peak

for the intrinsic material appearing at 0.7 ev. corresponding to
its room temperature energy gap. The addition of copper causes a
subsidiary peak to appear at about 0.6 ev.

When pn junctions in silicon and germanium
are operated in the reverse bias condition, light emission in the
visible part of the spectrum can occur. The light emission occurs
in the breakdown and pre-breakdown regions and has been observed
on grown and alloyed junctions with breakdown voltages varying from
10 to 156 volts. A grown junction in a silicon crystal with a
breakdown voltage of 40 volts emits a yellow light peaking at about
2 ev. and falling off rapidly above 2.5 ev. The light appears in
the form of spots estimated to be 10 microns or less in size. The
density of spots appears to depend on current density at low
current densities and is reproducible. At high current densities
(of the order of 4 amp/cm^2), regions of uniform brightness appear
with the brightness a sensitive function of current. Decay times
associated with the emission have not been precisely determined
but are less than 4 μ sec.

Emission can be stimulated by forward currents
in SiC crystals. The spectral range extends from about 4600 Å to
about 6000 Å with two peaks, one occurring at about 4700 Å and the
other at about 5300 Å. The emission can be observed at 77°K or
room temperature. The brightness increases with increasing
current density. At room temperature, the efficiency can be as
high as 2 x 10^{-6} photons/electron. At low temperatures, effi-
ciencies as high as 2 x 10^{-4} photons/electron have been observed.
At room temperatures, the decay times observed are of the order of
1 μ sec. The presence of iron in the SiC is very deleterious to
the emission as the Fe serves as a killer center.

Electroluminescence occurs in single crystals
of gallium phosphide under excitation by either AC or DC fields.
An order of magnitude increase in brightness is observed when
reverse currents are passed through the crystals as compared with
forward currents. Several bands have been observed depending on
the nature of the activators. Gallium activation results in an
orange emission beginning at about 4600 $\overset{o}{A}$. The addition of Zn and
Cu results in a brilliant red emission with a spectral range
extending from 6800 $\overset{\bullet}{A}$ to beyond 8900 $\overset{o}{A}$. No noticeable effect
upon the orange emission results from doping with impurity elements
such as C, Si, Ge, Mn or S. In addition to the red band, Zn doped
crystals exhibit a yellow-green band extending from 5300 $\overset{o}{A}$ to
6300 $\overset{o}{A}$ and peaking at about 5900 $\overset{o}{A}$. Decay times in these materials
are less than 25 μ sec.

Other III-V crystals exhibit electrolumines-
cence. Gallium antimonide at room temperature emits light in a
range from 0.7 ev. to 0.55 ev. with a peak near 0.62 ev. Current
densities up to 1 amp/cm^2 have been passed in the forward direction
by pulsing with a 50% on-off square wave generator operating at
100 cps. Similar operation on gallium arsenide crystals both at
room temperatures and 77°K yields a spectrum peaked at about 1.2 ev.
and extending to 1.6 and 0.8 ev. The low temperature spectral
response is somewhat sharper than the room temperature response.
Indium phosphide and germanium-silicon alloys have also been shown
to be electroluminescent. Detailed results of the spectral response
is not available in these cases; however, it is known that they
peak in the energy range appropriate to the gaps in these materials.
The energy gap in InP is 1.25 ev. and the gap in the Ge-Si alloy
varies from 0.7 to 1.10 ev.

Electroluminescence at contacts and in the
interior of crystals has been observed in aluminum phosphide and
on the nitrides of boron, gallium and aluminum. AlN gives
emission intensities which compare faborably with those found
in zinc sulphide. An activator such as Cu, Mn, or a group II
element is usually required to activate the material. The spectrum
consists of a series of narrow bands between 4000 and 5000 $\overset{o}{A}$ and a
broad continuous band from 5000 to 7000 $\overset{o}{A}$. Efficiencies are of
the order of 10^{-3} lamberts/watt.

Some II-VI compounds also behave as semi-
conductors and should exhibit electroluminescence under the
appropriate conditions. Cadmium telluide with an energy gap of
1.45 ev. has been observed to emit light when forward current is
passed through a pn junction in the crystal. The emission spectrum
does in fact peak at 1.44 ev. Thus far impurities do not seem to
affect the emission spectrum, although available experimental
evidence is rather sketchy.

c. Microcrystalline Phosphors

One of the most thoroughly investigated
electroluminophors is microcrystalline copper activated zinc
sulphide. Two emission bands are observed, one peaking at 4500 $\overset{o}{A}$
due presumably to the presence of the copper and the second peaking
at about 6500 $\overset{o}{A}$. As usual, the emission characteristics depend
in an important way on the method of specimen preparation. The
addition of co-activators such as aluminum, indium, and gallium
results in a phosphor which emits only green light providing the
copper concentration is sufficiently low. Phosphors activated

in this way are relatively frequency independent for excitation
frequencies from 60 to 15,000 cps. With copper and manganese both
present in ZnS, a strong electroluminescence is observed with a
peak at about 5850 $\overset{o}{A}$.

Zinc sulphide phosphors with copper as the
primary activator are strongly sensitive to the addition of
chlorine. A green band in addition to the copper blue band is
exhibited. The relative emission in the two bands is a sensitive
function of the copper, chlorine content and the temperature of the
specimen.

The effect which any particular activator
has on the spectral response depends, among other things, on the
band width of the parent lattice. The band width can be varied
by the use of solid solutions of different composition. ZnS - ZnSe,
ZnS-ZnTe, and ZnSe-ZnTe are systems of this kind and by means of
them a continuous range of bandwidths can be obtained from 3.6 to
2.1 ev. The ZnS-ZnSe system with copper as activator and chlorine,
iodine or bromine as a co-activator has been studied extensively.
By varying the percent of ZnSe in ZnS, emission peaks are possible
from 4470$\overset{o}{A}$ with no ZnSe present, copper as an activator and iodine
as co-activator to 6320 $\overset{o}{A}$ with no ZnS present, copper as an
activator and chlorine as co-activator.

Electroluminescence of ZnS phosphor sus-
pensions is possible under certain modes of operation under exci-
tation by constant fields. Normally, the emission is very weak,
but it is greatly enhanced by the addition of small amounts of
manganese impurity.

The more usual method of excitation employed
for microcrystalline phosphors is an applied AC voltage. ZnS:Cu,
Cl and ZnS:Cu, Al phosphors when excited in this way exhibit a
buildup time of about 10 msec. The brightness usually depends
exponentially on applied voltage. A normal brightness voltage
curve shows a relatively sharp knee at some critical voltage.
Below this critical voltage, very little emission occurs, while
above the critical voltage, the brightness varies nearly linearly
with voltage over a limited voltage range.

Considerable interest has occurred in thin
film phosphors. Several techniques have been used to obtain films
of thickness of the order of one micron. These films exhibit
electroluminescence at rather low applied voltages, as low as
2.2 volts at 1000 cps in fact. Under these conditions the
emission spectrum is independent of applied voltage. The light
output is nearly constant from 100 cps to 10,000 cps but decreases
sharply with increasing temperature. In some cases, excitation by
DC voltage is possible; in fact, brightness levels up to 600 ft. L.
have been observed with a DC applied voltage of 85 volts.

2. Photoconductivity

A photoconductor is a material whose electrical
conductivity can be increased by the absorption of light or other
suitable radiation. This property of matter has been known since
1873 and since then more than one thousand papers have appeared on
the subject or closely related topics. An excellent compilation
of references up to 1959 appears in <u>Photoconductivity of Solids</u>
by R. H. Bube published by John Wiley and Sons in 1960. No
attempt will be made here to give a detailed description or even

a thorough survey of the mountains of information available on the
subject. The course to be followed is merely to list those materials
which are known photoconductors and to present some remarks on the
characteristic properties of those materials.

A solid in thermal equilibrium has its
electrons (and holes) distributed among available energy states
in accordance with Fermi statistics. The deeper lying states are
bound states, i.e., localized in space, hence do not contribute to
conductivity. The intermediate states may be free and thus capable
of contributing to the conductivity, but in the case of insulators
and semi-conductors they are completely filled and, therefore, do
not contribute to the conductivity. The higher lying states are
free and unfilled; however, a certain fraction of these levels will
be thermally occupied leaving behind a like number of free holes
in the intermediate levels. These carriers give rise to a
temperature dependent "dark" conductivity. The absorption of
light upsets the equilibrium distribution by raising more electrons
from the intermediate levels to the unoccupied free states thus
increasing the conductivity. Of course, these electrons remain
in the excited state only until recombination processes return
them to their original ground states. This temporary increase in
conductivity induced by the photon-electron interaction is the
phenomenon referred to as photoconductivity.

To compute the magnitude of the photoconductive
current, it is only necessary to know the increase in free carrier
density induced by the incident photons. However, the free carrier
density will, for a given excitation rate, be dependent on the

lifetimes of the free carriers in the excited states. This leads to
the expectation that speed of response and photosensitivity should
be reciprocally related for intermittent light pulses. That this is
not the usual experimental observation suggests that recombination
can take place in a variety of ways. Indeed, it is necessary to
consider the effects of various discrete states in the forbidden
energy gap of insulators and semiconductors.

        The four characteristic properties of
importance for photoconductors are their dark conductivity,
spectral response, speed of response, and photosensitivity. The
dark conductivity depends on the energy gap of the material and
on the density and type of imperfections present in the material.
In insulators the density of free carriers due to thermal excita-
tion is extremely small as the energy gaps are quite large. In
semiconductors the opposite situation can occur as some semiconductors
have very small energy gaps. This intrinsic difference between in-
sulators and semiconductors vitally affects their respective
responses to photo-excitation and conditions of operation. For
example, insulating photoconductors can be successfully operated
at room temperatures while semiconducting photoconductors are
normally operated at low temperatures in order to reduce the dark
current. Room temperature dark conductivities in insulators are
less than about 10^{-6}/ohm cm while those of semiconductors usually
lie between 10^{-6}/ohm cm and 10^{2}/ohm cm depending, of course, on
the energy gap in the material.

        In a pure, perfect material, photons of
energy less than the energy gap are not capable of producing free
carriers and hence do not contribute to photoconductivity. This
leads to a sharp, low frequency cut-off in the photo-response curve

of the photoconductor. In practice a maximum response is usually
found at a photon energy close to that of the energy gap with a
subsequent fall off at higher energies. This decrease in response
can be associated with absorption at the surface of the photo-
conductor, a region of intrinsically lower photosensitivity than
the bulk region. The presence of impurities or lattice imperfections
introduces discrete levels in the forbidden gap and thus leads to
an additional response to light of energies less than the band gap.
In general a complex level scheme is observed. Since band gaps
range from 0.02 ev. in HgTe to energies greater than 5 ev. in
diamond, photoconductors sensitive to photons from the ultraviolet
to the infrared can be achieved.

In a pure, perfect material the speed of
response would be identical with the free carrier lifetimes. In
a real specimen the observed speed of response is several orders
of magnitude slower than is to be expected on the basis of the
free carrier lifetimes. These extended rise and decay times are
caused by the trapping of free carriers at the various trapping
centers which invariably exist in a real specimen. Trapping, of
course, extends the rise and decay times by temporarily holding the
electrons incommunicado, so to speak. That is, during excitation
it removes carriers from the free state thus lengthening the rise
time while during the decay process it slowly releases the trapped
carriers thereby extending the decay time. The nature and density
of trapping centers depends on the specimen treatment and the types
of impurities contained by the host. In general, a very wide varity
of trapping centers and associated photoconductor characteristics
can be achieved.

The photosensitivity of a photoconductor is
expressed in at least three different ways. One way is to state
the minimum detectable excitation required to give a signal equal
to the noise in the photoconductor. This definition of sensitivity
is principally used for infrared detectors. Photoconductors of
this type have sensitivities ranging down to 10^{-12} watt. A second
way to specify photosensitivity is to give the photocurrent per
unit light intensity at fixed applied field. Defined in this
way the sensitivity is called the specific sensitivity and has
the units of cm^2/ohm watt. In equation form the specific sensitivity
S is given by

$$S = \frac{\Delta i}{V} \ell^2 / P$$

where   i = photocurrent,

        V = applied voltage,

        ℓ = electrode spacing,

        P = absorbed radiation power.

The advantage of this definition is that S is
independent of cell geometry and light intensity provided the
photocurrent is a linear function of applied field and light
intensity. The most sensitive cadmium sulfide and cadmium selenide
photoconductors have specific sensitivities approaching unity; however,
most materials have specific sensitivities several orders of magnitude
smaller. A third way to define photosensitivity is to specify the
photoconductivity gain, i.e. the number of electrons flowing from
one electrode to the other per photon absorbed. This is often
called the quantum efficiency or quantum gain of the photoconductor.
Gains as high as 10^4 have been observed in cadmium sulfide photo-
cells although in general the gains are orders of magnitude less.
Typical photoconductor parameters discussed in the following sections
are listed in Table VI for reference.

TABLE VI

SUMMARY OF PROPERTIES OF TYPICAL PHOTOCONDUCTORS

HOST	TYPICAL IMPURITY	OP. TEMP.	TYPICAL PEAK EMISSION WAVE LENGTH	SENS.	RESPONSE TIME	COMMENTS
Se	Group III Acceptors Group V Donors	77°K	infrared	0.03-3 amp/lumen	1-10 μ sec	Photoconductivity discovered in Se
Ge	"		"	"	1-10 μ sec	Photoresponse varies from
Si	"		"	"	1-10 μ sec.	1×10^{-4} to 1 mho/watt
C	"		"	"	"	"
CdS	Group I,V Acceptors	RT		50 amp/lumen	1 m. sec.	Group II-VI compound
CdSe	Group III, VII Donors	"		"	0.5 m. sec.	Family has many members
ZnS	Cl,Br,Al, Sc Ga, In (Donors)	"	24800-49600A°			Addition of impurities shifts threshold from u-v to visible
ZnS	Cu, Ag (Acceptors)	"	12390-24800A°			
PbS		77°K	25,000A°	10^{-11} watt S/N=1	100 μ sec.	Low temperature
PbSe		77°K	60,000A°		10 μ sec.	Operation necessitated by relatively low energy gap.
PbTe		77°K	45,000A°		10 μ sec.	

a. Elements

Crystals of certain of the elements exhibit
photoconductivity; indeed, photoconductivity was discovered in
selenium. In addition to selenium, germanium, silicon, and
diamond are photoconductors. Point contact, pn junction and npn
junction phototransistors have been made using germanium and
silicon. The response times of these devices are of the order of
one to ten microseconds with sensitivities ranging from 0.03 to 3
amp/lumen. As the energy gaps are small, the spectral response is
in the infrared. The effects of impurities added to germanium and
silicon have been extensively studied. As both these elements are
group four, it is clear that group three impurities should act
as acceptors and group five impurities should act as donors.
Elements further removed from Group IV have in general more than
a single level and may act either as donor or acceptor or in some
cases as both. The Group III and V impurities usually have small
ionization energies and thus have correspondingly long wavelength
thresholds. Impurities such as B, Al, Ga, In and Tl from Group III
and P, As, Sb, and Bi from Group V when added to germanium or
silicon yield threshold wavelengths ranging from about 10 to over
100 microns. Most of the levels associated with impurities having
more than one level have larger ionization energies than those of
Groups III and V. Accordingly threshold wavelengths are shorter,
usually of the order of a few microns. Impurities such as Cu, Au,
Zn, Mn, Fe, Co, Ni and platinum when added to germanium yield
thresholds ranging from about four microns to nine microns.
Copper is an exception, yielding a threshold of 29 microns. When
added to silicon, impurities such as Cu, Au, Zn, Mn and Fe yield
thresholds ranging from two to five microns. The small energy
gaps in silicon and germanium require that these photoconductors

be operated at low temperatures, preferably at or below liquid air
temperatures. The photoresponse in these materials varies from 10^{-4}
to 1 mho/watt.

b. II-VI Compounds

A large number of photoconducting materials
belong to the Group II-VI compound family. Two of the most common
materials used as commercial photocells, cadmium sulfide and cadmium
selenide, are members of this family. Many of the oxides and sulfides
are known photoconductors including those of cadmium, zinc, mercury,
and barium. The sulfides of calcium and strontium are photoconductors
as well as the oxide of magnesium. Some of the selenides and
tellurides are photoconductors including those of cadmium.
Undoubtedly many more II-VI compounds are photoconductors and
information concerning their properties will appear in the literature
as time goes on. The impurity ionization energies in the II-VI
compounds are considerably larger than those in germanium and silicon.
Of course, the energy gaps of all II-VI compounds mentioned above
are considerably greater than those in silicon and germanium, hence
deeper lying trap states are possible. As a result, higher
threshold frequencies are found in these materials compared to
those observed in the germanium and silicon crystals. In general,
Group I and Group V impurities act as acceptors while Group III
and Group VII impurities act as donors.

Donor impurities such as Cl, Br, Al, Sc,
Ga, and In when added to zinc sulfide yield ionization energies
ranging between 0.25 and 0.50 ev. Acceptors such as Cu and Ag
have ionization energies between 0.5 and 1.0 ev., energies
comparable with the band gaps in silicon and germanium. Bromine,

acting as a donor in zinc selenide, has an ionization energy of
0.21 ev. while Cu, Ag, Sb and As, acting as acceptors, have
ionization energies from 0.6 to 1.3 ev. The donor levels intro-
duced by Cl, Br, I, Al, Ga, and In in cadmium sulfide all have
small ionization energies of about 0.03 ev. However, the acceptor
levels introduced by copper and silver have ionization energies
which are at least an order of magnitude greater. These impurities
behave very nearly the same in cadmium selenide. As these energies
are all quite large, the dark currents associated with these
materials are all very small. Consequently, photocells employing
these materials can be operated at room temperatures.

The threshold frequency in zinc sulfide is
in the near ultraviolet; however, the addition of impurities such
as Mn, Ag, and Cu move the threshold into the visible part of the
spectrum. On the other hand, the threshold frequency in CdSe is
in the near infrared while that of CdS is in the middle of the
visible spectrum. Additions of impurities such as copper and silver
shift the threshold to lower frequencies, hence cadmium sulfide
containing copper as an impurity has a peak response at about
6400 Å. The exact location of the peak in the photoresponse curve
depends on whether the specimen is single crystal or polycrystalline
and on the method of specimen preparation. Zinc selenide exhibits
a double peak when copper is added as an impurity. The major
peak is at about 4700 Å with the subsidiary peak at about 5100 Å.
On the other hand, when antimony is the impurity the subsidiary
peak appears more as a shoulder in the response curve extending
out to 10 or 11 thousand angstroms. At low temperatures the
shoulder is suppressed considerably and the main peak is
increased and sharpened somewhat.

Cadmium sulfide and cadmium selenide are two
of the most sensitive photoconductors known. Both have sensitivities
ranging up to 50 amp/lumen, several orders of magnitude more sensitive
than photoconductors. Associated with these high sensitivities,
however, is a long response time. The response time at high light
intensities is of the order of 1 msec in CdS and 1/2 msec at best
in CdSe. At low light intensities the response times are considerably
longer being of the order of fractions of a second to several seconds.

c. Other Inorganic Compounds

A great variety of other inorganic compounds
are known photoconductors. The most important of these are perhaps
the sulfide, selenide, and telluride of lead. The peak in the
photoresponse curves for these compounds fall approximately at
25,000; 60,000; and 45,000 Å, respectively. As these materials have
energy gaps less than 0.5 ev., the dark conductivity is very high
at room temperatures. Successful operation requires low temperatures,
preferably in the liquid air region. The sensitivity of these
materials is very good being of the order of 10^{-11} to 10^{-12} watts
for a signal to noise ratio of unity. The response times are very
good considering the high sensitivity of the materials. Lead
selenide and telluride both have response times of the order of ten
microseconds while lead sulfide has a response time of about 100 μ
sec.

Photoconductivity has been observed in a
large number of the halides. Most of these crystals are quite good
insulators, i.e. they have rather large energy gaps. Magnesium and
barium oxides also have large energy gaps and behave a great deal
like the alkali halides. The thresholds associated with these

materials in the pure state are all very high, being well into the
ultraviolet part of the spectrum. However, by proper treatment with
X-radiation or addition of suitable impurities additional bands can
be introduced in the energy gap. In this way it is possible to
sensitize the photoconductors to radiation in the visible part
of the spectrum.

The III-V semi-conductors are likely candidates
for photoconductivity. Both indium antimonide and gallium arsenide
are known photoconductors with peak response at 5 and 1 micron
respectively. As the energy gap in InSb is only 0.18 ev., it is
essential to operate at very low temperatures, in the liquid helium
range, in order to observe its photoconductivity. However, the gap
in GaAs is 1.4 ev., thus operation at much higher temperatures is
feasible for gallium arsenide photoconductors. The addition of
Cu, Ag and Au to indium antimonide increases the threshold to as
much as 20 or 25 microns; however, the increase is primarily in
the form of a shoulder at least two orders of magnitude below the
peak in the photoresponse curve.

d. Organic Photoconductors

Many organic compounds exhibit semiconductor
characteristics and thus are possible photoconductors. Energy gaps
in some organic materials fall in the range from 0.2 to 1.6 ev.
Many of them have gaps close to those of silicon and germanium and
hence the photoconducting properties might reasonably be assumed
to be similar. Anthracene with a gap of 1.6 ev. has been studied
extensively and the spectral response is consistent with the energy
gap. Several organic compounds containing condensed aromatic rings,
some dyes and proteins have been studied. The most sensitive of

the aromatic hydrocarbons appears to be authracene with photocurrents
in the 10^{-9} to 10^{-10} amp range. Sensitivity of other aromatic
hydrocarbons can be as much as five orders of magnitude less than
that for anthracene. The enormous number of organic compounds
available for investigation makes this a very fruitful field for
research, but for developmental purposes it would seem that
inorganic compounds hold more near term promise.

3. Double Activated Phosphorescence

Phosphors are substances which are capable of
emitting light after having been exposed to some kind of radiation.
The spontaneous emission occurring after excitation is called after-
glow or background and is strongly temperature dependent. In some
cases the emission can be enhanced by radiation different from the
primary excitation. This phenomenon is called stimulation or double
activated phosphorescence. In many cases the emission can be
diminished by radiation different from the primary excitation.
This phenomenon is called quenching.

These phenomena can be understood qualitatively
on the basis of the energy band theory of solids. At zero exci-
tation an insulator (or semiconductor) consists of a series of
filled electronic energy bands (Ref. Fig. 27a). The highest of these
filled bands is called the valence band. Above this band and
separated by a region called the forbidden region or energy gap
lies an empty band called the conduction band. Within the forbidden
region several types of energy levels can exist. These may be due
to impurities added to the host crystal or any of several types of
lattice imperfections. Assume two levels A and B are present in
the forbidden energy gap; further, suppose that B is a metastable
state, that is, the transition from B to the valence band is a
forbidden transition. An electron in the valence band can absorb

an incident photon and be excited (1) to the level A. Subsequently,
the electron might make a transition (2) to the metastable state B
where it remains trapped. Upon further excitation (3) to level A,
the electron makes the allowed transition (4) to the valence band.
This would be a case of stimulated emission.

An alternate way to understand these phenomena
is indicated by Figure 27b. Here the free energy of the system
is plotted against some appropriate configurational coordinate.
Curve A represents the ground state of the system while Curves B and
C represent two possible excited states of the system. Excitation
can take place either by 1) raising an electron from A to B or
1^1) raising an electron from A to C. After excitation (1) the
system readjusts itself by phonon generation until the minimum
in Curve B is achieved. This is followed by a transition to the
state A with the emission of a photon of the appropriate frequency.
This would normally occur almost immediately upon excitation and
this constitutes a fluorescence. On the other hand, after exci-
tation (1) the system, after phonon generation, arrives at the
minimum of Curve C. Now no further transition is possible unless
the system is stimulated in some way. Upon absorption of a photon (3)
of appropriate frequency, the system is excited to state B whence
the emission (2) is then possible. This illustrates qualitatively
the way in which stimulation or double activated phosphorescence
occurs. If a photon is absorbed resulting in transition (3), then
no photon emission can take place, but rather the energy will be
dissipated in lattice vibrations. This would be an example of
quenching.

The basic requirements for double activated
phosphorescence, as seen from the above discussion, are a material
with a filled valence band, an energy gap and at least two different

types of levels lying within the forbidden region. The number of
materials satisfying these conditions is infinitely large; however,
the number of satisfactory materials from a practical standpoint is
much smaller. The reasons for this are many, not the least of
which is the problem of producing any given material in a completely
reproducible manner. There are many instances reported in the
literature where two specimens prepared by apparently identical
techniques have produced rather divergent results. To make matters
worse, the proprietary nature of the subject has resulted in a
noticeable lack of a satisfactory compilation of phosphors and
phosphor properties. The net result is that a phosphor expert
with broad experience in the field of phosphor research and
development is essential in any program which envisions the use
of phosphors in any way.

In order to obtain the two types of energy levels
in the energy gap required for stimulated emission it is necessary
to add two activators to the host crystal. In this way a number
of infrared sensitive phosphors have been developed. One of the
activators, called the dominant activator, determines the emission
spectrum for a given host lattice. The second activator, called
the auxiliary or co-activator, determines the spectral distribution
of sensitivity to stimulation, by radiation, often called the
stimulation spectrum. As an example, strontium sulfide phosphors
with samarium as co-activator exhibit a stimulation spectrum which
peaks at about 1 micron. The emission spectrum, however, is found
to depend on the dominant activator. The peak in the emission spectrum
is 9.48, 9.49, 9.57 and 0.63 microns for dominant activators of
cerium, copper, manganese and europium, respectively. In a similar
manner the peak in the stimulation spectrum can be varied by using
different co-activators. The use of tin as co-activator results in
a peak at 0.63 microns while bismuth yields a peak at 0.88 microns.

The co-activator in many cases produces a second
important effect. It is found that the addition of the co-activator
considerably reduces the afterglow of the dominant activator. This
reduction in afterglow can be by as much as several orders of magnitude.
The reduction in afterglow is accompanied by an increase in storage
time.

Appreciable photostimulation is not observed in
phosphors which have only temperature independent exponential
emission decays. This is understandable as the type of decay is
characteristic of an unimolecular process and, as we have seen, for
stimulated emission two centers are required. Such a phosphor, however,
can be made stimulable by altering its composition. Thus rhombohedral
(rbhdl.) $Zn_2 GeO_4$: Mn can be rendered photostimulable by the incorpor-
ation of SnO_2. The phosphor $3ZnO. 2GeO_2. 0.06SnO_2. 0.02MnO$ emits a
green light upon stimulation by infrared light of the order of one
micron. The emission decay in this case varies as an inverse power
of time, characteristic of a bimolecular process.

The photostimulation and photoconduction of
phosphors is very closely related. In fact, the spectral distribution
of photostimulated phosphorescence is almost identical to the spectral
distribution of photostimulated photoconduction in many cases. This
is evidence of the fact that the same electrons are contributing
to both processes. In general, however, the stimulated phosphores-
cence decays much more rapidly than the stimulated photocurrent.

Several of the more common stimulable phosphors
are listed in Table VII. It is to be noted that these phosphors
are mainly stimulable by infrared radiation. This results mainly

TABLE __VII__

SUMMARY OF PROPERTIES OF TYPICAL DOUBLE
ACTUATED PHOSPHORS

Phosphor	Peak Wave Length of		
	Excitation A	Emission A	Stimulation A
1. Cub.Sr (S:Se): flux: Sm:Eu	4,600	5,700	9,300
2. Cub. SrS: flux: Sm:Eu	4,800	6,300	10,200
3. Cub. Ca(S:Se): flux : Sm:Eu	4,800	6,300	11,000
4. Cub. CaS flux : Sm:Eu	4,800	6,600	11,700
5. Cub. SrS: flux: Sm:Ce	2,900	4,800	10,200
	3,500	5,400	
6. Hex.ZnS:Cu:PbSO4: NaCl (2)	3,700	4,880	7,500 13,200
7. $2SiO_2$:CaO:Pb:Mn	*2,537	red-orange	11,000
8. $3SiO_2$:CaO:Pb:Mn	*2,537	white	10,000
9. ZnS:CdS:Cu:Mn	3,700	6,000	13,500 9,000
10. ZnS:Pb:Mn	3,700	5,900	13,500 9,000
11. 3ZnO:2GeO$_2$:0'06SnO$_2$: 0'02MnO		green	10,000

* Peak excitation used: not necessarily characteristic of the material
but probably reasonably close to the maximum for the material.

from the fact that a great deal of emphasis was placed on developing
infrared sensitive phosphors dating back to the 1930's. This does
not mean that phosphors stimulable by radiations other than infrared
radiation have not been or could not be developed. In fact, by
careful selection of host crystal, dominant activator and auxiliary
activator just about any combination of excitation, emission and
stimulation spectrum is possible. Of course, in addition to these
variables decay times and efficiencies are also of interest. In the
phosphor listed as Number 1 in Table VII the efficiency is found to
be strongly dependent on the relative amounts of SrS and SrSe present
in the specimen. The addition of CaS also affects the efficiency
of this particular phosphor. These effects are not thoroughly
understood, hence we have no way of predicting the results for
a particular phosphor. This emphasizes the fact that phosphor
development is a very delicate art requiring the resources of a
phosphor expert of extremely broad experience.

Storage times in the phosphors vary considerably
from one phosphor to another, but can easily be of the order of
days. In addition, the storage times depend in an important way
on the temperature of the specimen. Many of the double activated
phosphors can be thermostimulated to an appreciable extent at room
temperatures. Others do not show appreciable thermal stimulation
until rather high temperatures are achieved. While there is some
relationship between the thermal stimulation and photostimulation
energies, they are not necessarily equal. In fact, the energies
required for thermal stimulation are normally less than those
required for photostimulation. This can be understood in a very
simple way. In photostimulation the momentum of the electron
being excited is conserved. Thus a vertical transition in

energy momentum space takes place (Reference: Figure 27a, transition 1).
On the other hand, for thermal stimulation the electron makes a
transition from an energy band minimum to an energy band maximum
(as in Transition 2, Figure 27b. Clearly these will only be equal
if the minimum of Band B lies directly above the maximum of Band A,
while in general 2 will be less than 1.

The phosphor listed as Number 5 in Table VII and
commercially referred to as Standard VII has been widely used in
devices called snooperscopes and sniperscopes. In addition to being
one of the most sensitive infrared phosphors, the peak of its
excitation spectrum lies in the invisible ultraviolet. Since it is
essential that the devices mentioned operate with invisible radiation,
this property of Standard VII has made it particularly useful. For
use in an image transducer however, this property may in fact be
undesirable. A phosphor such as Standard VI (listed as 2 in Table
VII) probably would be more desirable since the peak of its
excitation spectrum lies at 4800 $\overset{o}{A}$ in the visible part of the
spectrum.

From Table VII it is clear that the excitation
peak wavelength is less than the emission peak wavelength, which,
in turn, is less than the stimulation peak wavelength. With
reference to Figure 27,   it is clear that the excitation peak
wavelength will normally be less than the emission peak wavelength.
Furthermore, it is reasonable to expect the emission peak wave-
length to be less than the stimulation peak wavelength. These
facts have an important bearing on any potential application of
these materials. As an example, suppose a device were desired to
be capable of excitation by light in the near infrared. If the
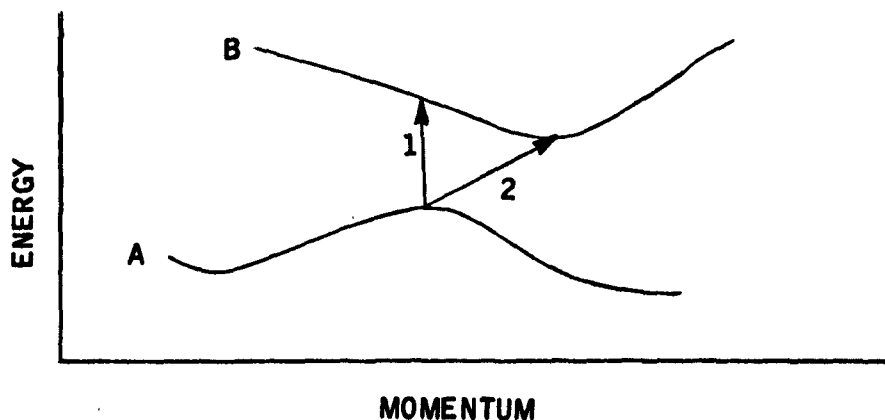device were to operate in the normal excitation, stimulation,

CONDUCTION BAND
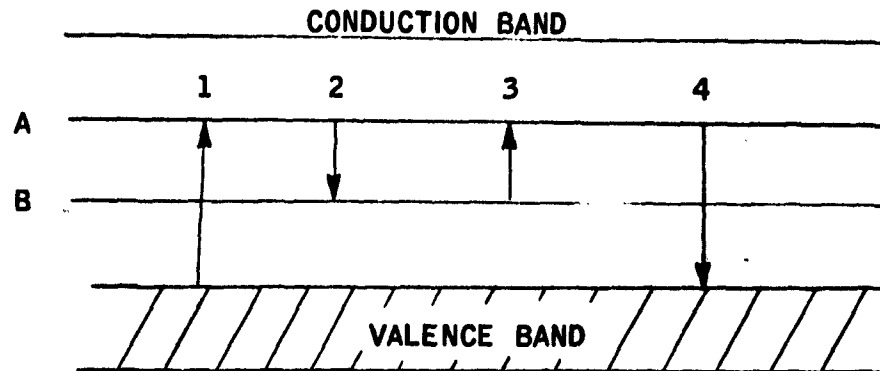
EXCITATION-STIMULATION SCHEME ON THE BAND
PICTURE FOR DOUBLE ACTIVATED PHOSPHORESCENCE   (A)
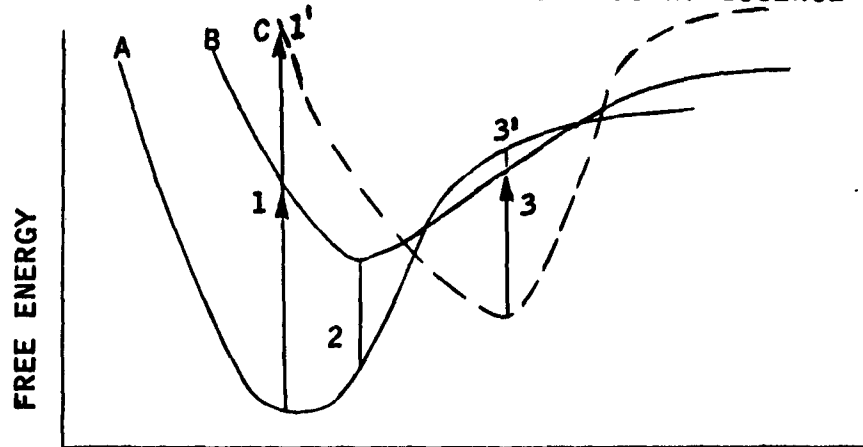
CONFIGURATION COORDINATE

PHOTOSTIMULATION AND PHOTOQUENCHING ON THE FREE   (B)
ENERGY-CONFIGURATION COORDINATE PICTURE

MOMENTUM

PHOTOSTIMULATION (1) AND THERMAL STIMULATION (2) PROCESSES (C)

R-14,562

FIGURE 27

emission mode, the stimulation and emission wavelengths would probably
be in the far infrared. In all likelihood this would be a difficult
device to construct even if the material problem could be solved,
as the device would have to operate at extremely low temperatures.
A possible solution to a problem such as this would be to consider
a slightly different mode of operation, for example, excitation,
partial stimulation (accompanying emission not used), complete
stimulation, and emission. This mode of operation would yield a
negative image.

4. Phototropism

The chemical part of the literature survey was
concerned with finding compounds whose properties have been des-
cribed by terms such as photochromic, phototropic, tenebrescent,
and evanescent. These adjectives have been used by various investi-
gators at various times to describe materials which change color when
exposed to radiation in a particular spectral region and which revert
to the original color when placed in darkness or when exposed to
radiation in a different spectral region. In accordance with
current usage the term "phototropism" will be used in this report
to designate such phenomena. The phototropic mechanism may be of
a chemical or of a physical nature but generally it embraces both
fields of science. This part of the literature survey report deals
with materials whose phototropism is primarily of a chemical nature.

For the current image transducer concept the
photosensitive material should display the following characteristics:

    1. The material should change color (the term "color"
        in this report includes the near ultraviolet, 300-400
        $m\mu$, and the near infrared, 700-800 $m\mu$.) when exposed

      to radiation of a given spectral characteristic,
preferably in the visible portion of the spectrum.
(activation or read-in).

2. The material should retain this induced color until
   exposed to radiation of a different spectral charac-
   teristic at which time it should revert to its
   original colored (or colorless) state. (erasure).

3. The material should be insensitive to a third portion
   of the spectrum so that the extent of the color change
   may be determined by measuring the transmittance (or
   reflectance) of the material in this spectral range.
   (read-out).

4. In the spectral region utilized for measurement (read-out)
   there should be a large difference between the molar
   extinction coefficients of the activated and the un-
   activated forms of the material. The absolute value
   of one form should be as high as possible so as to
   generate an intense color for a given input energy.

5. The speed of the activation color change should be very
   fast, preferably in the microsecond range or lower. The
   speed of the erasure change may be several orders of
   magnitude slower.

6. The quantum efficiency of the activation reaction should
   be high so as to achieve a high sensitivity.

      Since scientific literature seldom deals with photo-
sensitive materials from these points of view, it was necessary to
attempt the evaluation of the properties of a material from whatever
type of data was presented. Properties such as: The complexity of
the reactions; the number of intermediate products; the existence

of side reactions, decomposition, etc.; the order of the reaction
(unimolecular, bimolecular); velocity and equilibrium constants;
temperature coefficients; physical state (crystalline, amorphous
solid, solution, rigid media, etc.); were useful but not conclusive
criteria in considering the utilization of the material in the
image transducer application.

    Basically the photochemical primary processes
that may take place following the absorption of a photon by a
molecule are:

1. Fluorescence emission of the absorbed radiation.
2. Deactivation by collision with other molecules.
3. Direct dissociation into simpler molecules, atoms
   or free radicals.
4. Dissociation caused by collision with other molecules.
5. Internal rearrangement (isomerization).
6. One or more different reactions with normal molecules.
7. Transfer of energy to normal molecules by means of
   inductive resonance transfer.

    These primary processes are limited to a maximum
quantum yield of 1, but they may be followed by secondary reactions
giving a very high overall quantum yield. For the proposed image
transducer applications the literature search for chemical materials
was directed towards substances exhibiting photochemical processes
such as #3, 4, 5, 6, and 7.

    Phototropic materials may be divided into two
categories, organic and inorganic. In both classes the phototropic
phenomena may occur in the solid state as reported in most of the
earlier literature, or in solution as described in more recent

investigations. In general, solid materials require from a few seconds
to many minutes to develop a pronounced change in color, and require
from a minute to several weeks for the reverse change. Solutions on
the other hand generally develop a color change in from microseconds
to seconds and undergo the reverse change in from seconds to several
days.

Four previous surveys of the literature dealing
with phototropism have been made: 1. Stobbe[2] reviewed the field
through 1921; 2. Chalkley[3] through 1928; 3. Bhatnagar, Kapur, and
Hashmi[4] through 1938; and 4. Brown & Shaw[5] through 1959. Brown and
Shaw's survey reviewed the literature covered by Chemical Abstracts
through 1959 for materials showing reversible color changes. The
current survey reviews that of Brown and Shaw, covers Chemical
Abstracts from 1959 through 1962, and includes additional infor-
mation derived from patent files.

Among the classes of organic compounds which show
phototropy are: anils , disulfoxides, fulgides , hydrazones,
osazones, semicarbazones, stilbene derivatives, hydrazides, spiro-
pyrans, azo dyes, nitro stilbenes, dinitrobenzyl derivatives, and
triphenyl methane derivatives. Considering application to the
image transducing system, most of these materials for which pertinent
data were given were judged to be of little promise for one or more
of the following reasons:

      1. The color forming reaction was attended by non-
          reversible side reactions. This leads to rapid
          fatigue (loss of phototropic properties) as an
          increasingly large amount of the active material
          is converted into non-active side products.

2. The color forming reaction involved a number of
    intermediate steps (or products) before yielding the
    final desired product. Depending upon the velocity
    constants and the equilibrium constants of the inter-
    mediate reactions, the time of formation and the
    yield of the desired colored product were limited
    by the least efficient reaction.

3. The reverse color change proceeded spontaneously
    rather than being effected by exposure to the erasure
    radiation. If the spontaneous reversion to the
    unactivated state were slow enough, the material
    might be useful for limited time storage, but most
    substances underwent the reverse color change very
    rapidly, with some in terms of microseconds.

4. The forward or reverse reaction was temperature
    dependent in an adverse manner.

5. Only a very weak color change was produced. This
    could be caused by
    a) low extinction coefficients in the visible
        part of the spectrum
    b) a low quantum yield
    c) unfavorable equilibrium conditions between the
        forward and reverse reactions

6. The activation (color forming) reaction was very slow.
    This could indicate a very low quantum yield.

7. The erasure (color bleaching) reaction was very slow.

8. The phototropic phenomenon took place only in solution,
    thus making impractical an image forming surface with
    good planimetric resolution.

The organic materials which exhibit phototropy
are much more numerous than the inorganic substances. Among the

latter can be listed: alkaline earth sulfides and titanates,
alkali halides, complex mercury salts, zinc sulfide, copper
halides, bismuth oxalate, cadmium iodide, titanium oxide, rare
earth chelates, molybdenum oxides, coordination complexes of
chromium, and minerals of the sodalite family, especially pink
hackmanite. These inorganic compounds all exhibited undesirable
characteristics for application in an image transducing system.
In addition to the objectionable characteristics listed for
the organic compounds, many of the inorganic were phototropic
by virtue of an oxidation-reduction type system. In such cases
the phototropic reactions are dependent upon a continuing
supply of oxidizing agent (such as atmospheric oxygen) or
reducing agent. As soon as the oxidizing agent or reducing
agent is exhausted the phototropy ceases.

Since none of the materials reviewed were parti-
cularly promising in all respects for use as the photosensitive
surface of the image transducer, it was decided to determine what
materials might be useful with a minimum of compromise between
the desired properties and the existing ones:

(1) Pink hackmanite, as previously reported, gives
a fairly good coloration when exposed to ultra-
violet radiation. The color is stable indefinitely
and can be erased with radiation in the visible
portion of the spectrum. It shows no apparent
fatigue in over 350,000 cycles between the
activated and erased states. Its major disad-
vantages are very low sensitivity (low quantum
yield) for both the activation and the erase
reactions, and the inability to fabricate it in
a suitable form (thin transparent layer with uniform

sensitivity). If the latter objection can be
overcome, hackmanite could be used for an image
transducer of low sensitivity, with a possible
improvement in sensitivity if the "F-center" site
formation can be increased.

(2) Cinnamaldehyde semicarbazone[6,7] and derivatives
are phototropic in the following manner: The
colored form generates slowly (overnight) and
spontaneously in the dark, and is erased more rapidly
(minutes) in strong white light. It is reported
that the phototropic cycle can be repeated inde-
finitely. If the erasure time can be decreased,
this material would be suitacle for a low
sensitivity "single shot" image transducer giving
a positive image by visible light. The applica-
tion of heat may speed up the color generation
reaction thereby making possible more rapid
image-erasure cycles.

(3) Some spiropyrans[8,9] at low temperatures (-60°C)
upon irradiation with ultraviolet light form an
intense coloration which is stable until erased
by irradiation with visible light. The process can
be repeated indefinitely. These materials could
be used in a low sensitivity image transducer with
the proper implementation for keeping the photo-
sensitive surface cold. Alternatively, further
synthesis of new spiropyrans may produce one whose
spontaneous erase reaction proceeds at a negligible
rate at room temperatures thus making possible
operation without refrigeration.

Other materials with similar potentialities
exist in the literature but require additional experimental
evidence in order to evaluate their capabilities. The photo-
tropic mechanism by which most of these materials work falls
more in the field of solid state physics than in true chemical
phenomena. Since true chemical mechanisms that are reversible
in the sense necessary for the image transducer applications
are limited to a maximum quantum yield of one, it is felt that
the material required for a highly sensitive image transducer will
have to depend upon physical energy state transitions with its
attendant possibilities for energy amplification, rather than
upon chemical reactions.

5. Discussion

The material study has been based on a need
for materials (a) capable of converting an optical signal to
an electrical signal, (b) capable of image retention, and (c)
capable of converting an electrical signal to an optical signal.
Photoconductors are capable of accomplishing function (a), i.e.
conversion from a photon signal to an electrical signal. This
can be accomplished in several ways depending on the mode of
operation. The most useful way is to take advantage of the
change in conductivity produced in the photoconductor by
incident radiation. There are several types of materials and
processes capable of accomplishing function (b); however, for
the purposes of this study many are not applicable as the
image transducer requires erasable image retention. This
requirement, for example, eliminates the usual photographic
process as erasure requires regeneration of the emulsion.

Many of the photochemical processes are similarly eliminated,
leaving as the most useful materials those exhibiting double
activated phosphorescence or phototropism. Of course, it is
possible to accomplish image retention by combining a photo-
conductor (for optical to electrical conversion) with some
other material to provide a memory cell. The optron is an
example of such a device. Again, there are several ways to
accomplish function (c); but the requirements of the image
transducer under study eliminates many of them. Electro-
luminescent materials appear to hold promise for purposes
of this application.

a. <u>Conversion of an Optical Signal to an
Electrical Signal</u>

The first step in the image transducer
will be to receive an incoming optical image (signal). The
method used to receive the signal will depend upon the image
transducer's ability to accomplish its several assignments.
Ideally the transducer should immediately convert the optical
image into an electrical image for transmission. Such a device
does not appear to be possible in view of the system require-
ments for exposure time. To compensate for this certain devices
assigned other functions can be added to the system to accomplish
the desired task. In all conceivable systems, however, it is
necessary at some point to convert the optical signal to
an electrical signal. This can be accomplished by one or
another of the various photoeffects associated with photo-
conducting materials. The most important of these effects is
that of photoconductivity itself; however, other photoeffects
such as the photovoltaic, photoelectric, Dember, and photomagneto-
electric effects might be employed. Both the Dember and

photomagnetoelectric effects can be considered as photovoltaic
effects. The photovoltaic effects are primarily of concern
in conversion of solar energy into electrical energy. The
maximum efficiency of conversion achieved is of the order of
6%, obtained using Si and GaAs cells. Although energy conversion
is important for application in the image transducer, other
criteria must be met. The image transducer will not operate
under steady state conditions (as does a solar cell), but
rather under pulse conditions. Consequently, an important
parameter for any potential material is the response time.
The photovoltaic effects all have relatively long response
times as the processes all require the buildup of voltages by
minority carrier diffusion. In this respect photomultipliers
(employing the photoelectric effect) and devices employing
photoconductors are more nearly satisfactory. With reference
to Table VI it is noted that microsecond response times have
been achieved in photoconducting materials such as silicon,
germanium and diamond. Response times of less than a micro-
second have been observed in InSb. Such speeds are also
easily achieved with photomultiplying tubes. In view of these
facts the materials study*) has been primarily directed towards
photoconducting materials to accomplish the function of
conversion of an optical signal to an electrical signal.

b. **Image Retention**

For reasons covered in the First Quarterly
Report it is necessary to retain the received image in the
transducer. Ideally this would be done optically, although if
necessary it could be done after optical to electrical conver-
sion. Optical storage does, in fact, appear possible by means

*) Photomultiplier tubes which are adequate are readily available;
therefore no materials study is required on this aspect.

of double activated phosphors or phototropic materials. Other
means, such as photographic, are possible methods of optical
image storage; however, there are other system requirements
to be met. In particular, the process should be erasable and
have at least a moderately short response time, or more likely,
a very short response time. In both respects the double
activated phosphors and phototropic materials appear to be
satisfactory. Erasure is easily accomplished and both have
at worst moderately short response times. In addition to the
response times and erasure feature the materials should be
rather sensitive to incoming radiation (both visible and
infrared, presumably). Some fairly sensitive infrared stimu-
lable phosphors have been achieved.

Certain other image retention techniques
can be used. Most would require conversion of the optical
signal into an electrical signal first with subsequent storage
of the electrical image. Further conversion of the electrical
signal into a magnetic signal could also be employed with
subsequent storage of the magnetic image. Such multiple
conversion techniques probably unnecessarily complicate and
expand the device. This expansion and complication would un-
doubtedly exhibit itself in increased size, weight and cost of
the device. Thus electrical to magnetic conversion has been
ruled out. Storage of the electrical image, on the other hand,
may be feasible. A prototype of a device employing a thin
layer of ferroelectric in conjunction with photoconductive
materials has been shown to be capable of readin, storage and
readout. The ferroelectric material performs the function of
image retention in the device. Resolution and speed of the

device is less than that of the usual vidicon technique. Further
investigation concerning the capabilities of materials of this
type are needed to understand whether or not the limitation is
one of fabrication technique or a fundamental material limita-
tion.

           In view of the foregoing discussion it
was decided to emphasize, during the present reporting period,
the investigation of double activated phosphors and phototropic
materials for possible use in an image retention device. Sub-
sequent investigations should be expanded to include a more
thorough consideration of the capabilities and limitations of
such materials as ferroelectrics for use in an image retention
device.

        c.   Conversion of an Electrical Signal
           to an Optical Signal

           There are several ways in which an elec-
trical signal can be converted into an optical signal. Many
of these, however, do not meet the requirements of the proposed
image transducer. Such methods as thermal radiation from a
heated element or gaseous discharge are undesirable for
several reasons. Power requirements are high, resolution is
poor, response times are much too long and system requirements
in general are undesirable. In all these respects the electro-
luminescent materials (so called cold light sources) are quite
adequate. Particularly those materials exhibiting injection
electroluminescence appear to have desirable properties. Over-
all efficiencies are surprisingly good and response times are
very short. Light emission in nearly any segment of the

spectrum from ultraviolet to far infrared appears feasible by
suitable doping of the electroluminescent materials. Power
requirements are very modest and high resolution devices are
a distinct possibility.

The use of materials capable of conversion
of an electrical signal into an optical signal suggests the
possibility of construction of a matrix light source. Such a
light source could be used as a digital readout device in
conjunction with an image retention component (employing a
double activated phosphor, for example). For these reasons,
considerable effort has been expended in examining the capa-
bilities and properties of electroluminescent materials.

C. EXPERIMENTAL INVESTIGATION

In order to fully evaluate hackmanite and other tenebrescent materials, and thus assure a complete investigation, Marquardt has initiated experiments to determine a means of fabricating these materials in a suitable form. This form must have optical transparency in the unexcited state and durability in the form of thin films.

The method of preparing hackmanite samples conceived at TMC will exploit the use of high pressure-high temperature and electrical techniques. It should be noted that in the materials literature survey, no such method was found.

As a first step, the preparation of available and convential "F" center" materials - such as hackmanite and the alkali metal halides has been attempted. The initial experimental phases were aimed at producing 1) clear thin wafers of potassium bromide 2) similar wafers containing a band of transparent layer hackmanite powder, and 3) thin wafers of fuzed hackmanite.

After a study of the optical properties resulting from the use of high pressure, high temperature processing, the second step will be the preparation of thin films of special "F-center" materials to obtain desired properties.

As has been indicated, one objective of recent experimental work was to change the physical properties of hackmanite without changing its optical properties.

Many times, the optical properties of solid materials

can be best studied when these material are embedded in a potassium
bromide wafer. Attempts have been made at TMC to prepare samples of
hackmanite by this method. Also, suitably doped potassium bromide
itself is a potential "F center" material. Therefore, its use herein
was obvious.

The materials used for the first experimental fabricating
work consisted of laboratory grade, chemically pure potassium bromide
and a small quantity of natural hackmanite. The optical properties of
different pieces of the latter were observed before and after reduction
to the powdered form necessary for the high pressure, high temperature
mold.

The observations confirmed literature information - such
as orange fluorescence under ultra violet exposure, bleaching under
white light, and pinkish colors under other conditions. Figure 28
presents a photograph of the UV Exposing Unit made for exposing various
samples to UV light at various density levels. Repeated observations
showed consistent results.

Initial work was accomplished in the 50 ton vacuum hot
press shown in the photographs of Figures 29 and 30. The first
exploratory preparation consisted of a two layer sample in silver
dichloride. One layer contained a pea sized flake of hackmanite,
another layer a mixture of powdered hackmanite and potassium bromide
in a weight ratio of

$$W_h \Big/ W_{KBr} = 30/70$$

These materials were held one hour at ten thousand atmospheres and
190°F.

Post run examination showed that the flake was undamaged
as expected but that the powder was not fuzed into a transparent media.
These results indicated the necessity for a wide range of mold setups
to optimize the results.

LIGHT SOURCE

BLOWER

FILTERS

SAMPLE
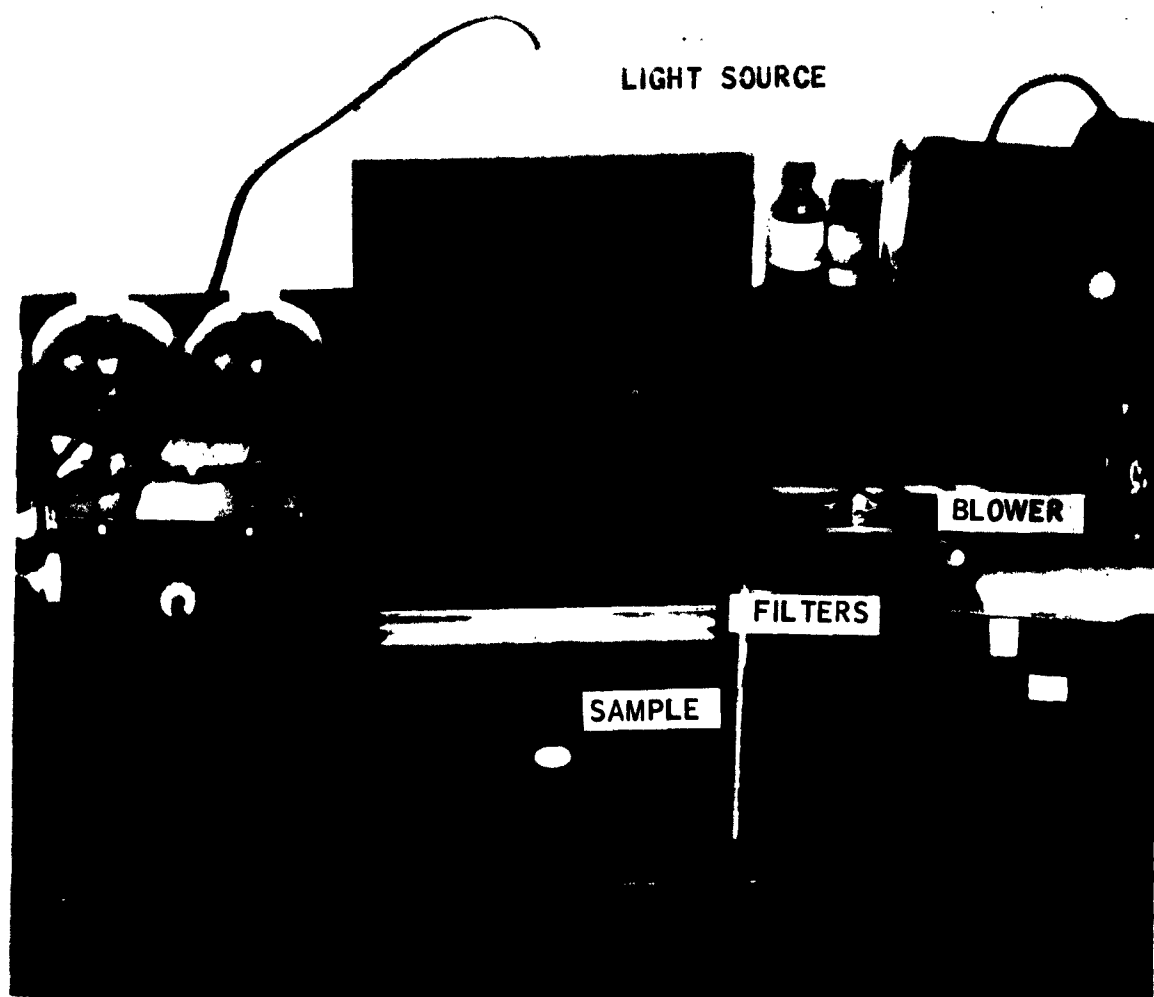
ULTRAVIOLET EXPOSING UNIT

FRONT VIEW

HOT PRESS

VACUUM SOURCE
AND
HEATER SUPPLY

GRAPHITE LAYER PRESSING EQUIPMENT   OVERALL

PISTON-CYLINDER
ASSEMBLY

GRAPHITE   LAYER   PRESSING   EQUIPMENT   CLOSEUP

4136-17
R-14,568

FIGURE 50

Accordingly, several subsequent setups (at lower pressures combined with a range of outgassing and temperature treatments) led to clear 1/8" thick wafers of KBr but scarred the polished surfaces of the mold fixture before a completely satisfactory hackmanite sample was produced. A total of 14 tests were made with the last establishing pressing conditions which appear to have satisfactory results.

Figure 31 is a photograph of four 1/8" KBr wafers showing the progressive improvement. The black shadows on the samples on the right are caused by surface contamination due to molybdenum disulphide which was used to eliminate sticking.

During the next reporting period, the fixture will be repared and more hackmanite will be obtained to explore the probability of making wafers without KBr.

Subsequently the series of experiments will be continued to determine the limiting properties of "F-center"coloration. This will include an extension of the experiments of Pohl & Hirsch (Reference 10) using KBr with and without HBr.

In these Marquardt experiments a crystal sample will be heated to about 1000°F in the high pressure fixture - but with the pressure not applied. At this temperature, a direct current will be applied. The combination of electrolytic and electronic conduction (especially with a mixture containing hydrogen bromide) will form a non-stoichiometric halide due to differential diffusion rates and reduction of the metal ions. At this point, an application of pressure should freeze the crystal in an optimal condition for "F"-center" phenomena.
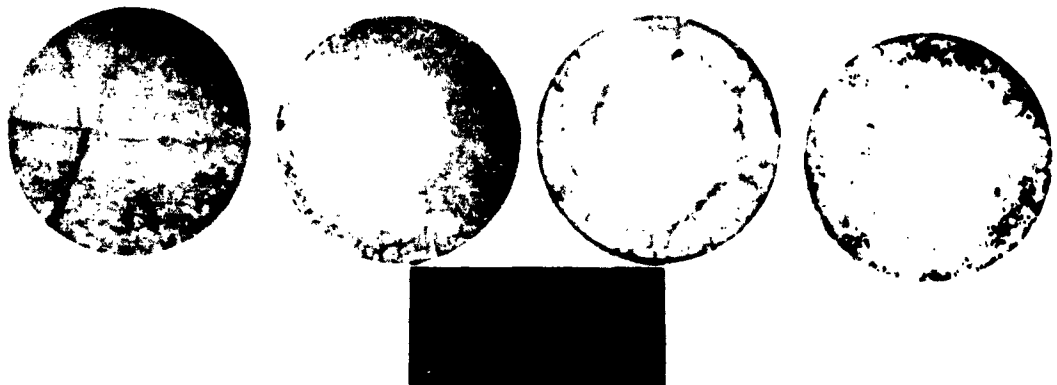
POTASSIUM   BROMIDE   WAFERS

/

D. RECOMMENDATIONS

The material study work has supplied sufficient
information on electroluminofors, photoconductors, double activated
phosphors nd phototropic materials to lend direction to the
development of a system concept. During the next quarter, the
following areas should be accented:

(1) Literature survey for ferroelectric materials which
show promise for image retention.

(2) Experimental investigations on materials displaying
($e[n]$) phenomena.

(3) The experiments on the preparation of a suitable
hackmanite specimen shall be continued along the
lines suggested by the preliminary results recorded
in this report.

E.   REFERENCES

Literature Survey

For a complete list of references refer to Appendix A of the first Quarterly Report and the tabulations in Electrolumir·scence by H. K. Henisch, published by Pergammon Press. in 1962 and Photo conductivity of Solids by R. H. Bube, published by John Wiley and Sons in 1960.

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V.   <u>CONCLUSIONS</u>

(1) It is now possible to define the performance characteristics of image transducers for various missions based on analytical studies of scene composition, and a survey of the current state-of-the-art. These results will assist in establishing design criteria for an advanced photo facsimile transmission system.

(2) The number of resolving elements for image readout can be increased by use of a technique which converts the raster scan into a single scanning line with orthogonal scanning accomplished by introducing relative motion between the image and the line.

(3) Regenerative image retention can be accomplished through the use of a combination of materials such as a photoconductor and electroluminor (the optron) or a photoconductor and ferroelectric (the ferrotron).

(4) The fabrication of an ordered fiber optic array for high resolution readout is not feasible at the present time because the development of fiber forming equipment capable of accurate positioning of very small diameter fibers in the vast numbers required is beyond the current state-of-the-art.

(5) Materials exhibiting electroluminescence, double-activated phosphorescence, photoconductivity, and ferroelectricty are promising for image transducing. Phototropic materials show too slow a response for the contemplated system.

(6) Natural hackmanite has characteristics (such as poor sensitivity and lack of clarity) which make it unsuitable for use in an image transducer. Experiments designed to overcome these shortcomings are required.

VI.   PROGRAM FOR NEXT INTERVAL

A. SYSTEM ANALYSIS

The studies of image transducing parameters and their inter-
relations will be continued in order: (1) to delineate parameter trade-off
possibilities (2) to establish ranges for the parameters based on
practical limitations and desirable performance characteristics for
various missions and (3) to establish design criteria for an advanced
image transducer.

B. COMPONENT RESEARCH

A matrix light source selection system for switching,
programming and selecting the light source elements will be evolved and
its cost and practicality evaluated. This switching system should also
be applicable for the electronic matrix readout.

The analysis of concepts for image retention and readout
utilizing the results obtained in the previous material literature survey
and in the state-of-the-art survey of image transducers will continue.
Specific solid state devices will be analyzed.

C. MATERIAL STUDY

Analytical and experimental investigations to select an
image transducing material for further development will be continued.
This will include an evaluation of the materials included in this
quarterly report. Further experiments will be conducted with synthetic
hackmanite. The study and analysis of ferroelectric materials which
show promise for image retention will be continued.

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